

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS

RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF

N.V. PHILIPS' GLOEILAMPENFABRIEKEN

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, HOLLAND

METALS AS GETTERS

by J. D. FAST.

621.528 : 546.431 + 546.831

In order to obtain the required high vacuum in radio valves, X-ray tubes, etc. and especially in order to maintain the vacuum after sealing off, use is made of metals which take up gases and hold them fast. Barium and zirconium in particular are used for this purpose. The properties upon which the action of these getters is based is discussed. In the case of barium and related metals it is a question of a chemical corrosion of the metal with the formation of a new phase, whereby the essential point is that the corrosion is always progressive (in contrast to what is desired in the case of corrosion-resistant metals), due to the fact that no dense surface layer of reaction products is formed. In the case of zirconium the action as getter is based upon the remarkably high solvent capacity of the metal for most gases encountered. In conclusion several details about the application of the getters mentioned are discussed.

Introduction

In the manufacture of electric lamps, radio valves, X-ray tubes, etc. the removal of air and other undesired gases from the bulbs or tubes is an important process. The evacuation by means of high-vacuum pumps is generally not sufficient, especially because the walls and electrodes of the tubes always contain all kinds of gases, such as oxygen, nitrogen, hydrogen, etc. as such, or in the form of decomposable compounds, and during operation these gases, due partly to the heating of the tube, may be freed and thus destroy the vacuum.

This is combatted during manufacture by heating the valves on the pumps to such a temperature that the gases present in the walls, etc. are freed as far as possible. Nevertheless, the possibility always remains that small quantities of gas will be freed during operation. In order to render this gas harmless, "getters" are employed. Getters are substances which are introduced at suitable spots in the tubes to be evacuated, and which, like the walls and electrodes, are able to take up gases, but with this difference, that the gases are so firmly held by the getter that they can no longer be freed under the conditions prevailing during operation, which is after all the essential point. The getter thus acts, as it were, like a high-vacuum pump permanently connected with the tube. At the same time it makes it possible to shorten the

pumping time in manufacture and to obtain lower gas pressures than is possible with ordinary high-vacuum pumps.

The oldest getter, and one that is still used in incandescent lamps, is phosphorus. For radio valves and X-ray tubes this substance cannot be used, because much higher vacua are required in these cases (phosphorus has a relatively high vapour pressure). In the latter cases, metals are used as getters, nowadays especially barium and zirconium. In this article we shall explain why just these two metals are especially suitable as getters. There will also be an opportunity of going somewhat deeper into the processes which take place upon the action of gases on metals in general.

The chemical corrosion of metals by gases. Barium as getter

The requirement that the metal which is to be used as getter must be able to bind quickly and completely the above-mentioned gases, such as oxygen, nitrogen, etc. may also be expressed by saying that the metal must be easily attacked or corroded by these gases. The getters are, therefore, as it were, the antipodes of the corrosion-resistant metals so important technically¹⁾. This contrast will be elaborated in the following.

¹⁾ We are here considering only corrosion by gases and not by liquids.

In order to be easily corroded by the gases mentioned, the getter must in the first place fulfil the chemical requirement of possessing great affinity to oxygen, nitrogen, hydrogen, etc. As a measure of this affinity, in most cases, and as an approximation, the heat of formation of the metal-gas compounds may be taken. If we take for instance the reaction with oxygen, then the requirement is that the oxide of the metal which is to be used as getter must have a large heat of formation. There are, however, various metals, such as aluminium, tantalum, etc. which satisfy this requirement, but which are nevertheless very stable in an atmosphere of oxygen. A great affinity to the different gases is therefore not sufficient to insure the satisfactory action of a metal as a getter.

If we consider the example mentioned, the corrosion of a metal by oxygen, somewhat more closely, it is found that in general the oxide is formed as a solid film on the surface of the metal. If this film is dense and coherent, further oxidation involves a diffusion of one of the reacting substances (or both of them) through the layer. At room temperature such a transport of material in the solid state scarcely takes place at all, the reaction therefore practically comes to a stop after the formation of a thin film of oxide. A dense coherent oxide film thus protects the metal against further oxidation.

If, however, the oxide layer formed possesses pores and cracks, the gas can reach the underlying metal by these paths without a diffusion in the solid state being necessary. In this case therefore the oxidation is able to progress, the oxide layer grows with time.

According to a rule proposed by Pilling and Bedworth²⁾ a coherent oxide layer is formed when the volume of the oxide is greater than that of the metal oxidized. If the volume of the oxide is smaller, pores and cracks appear in the layer³⁾. Also when other non-metals than oxygen act on a metal, dense or porous surface layers are formed according to the metal attacked, and the above-mentioned rule seems to hold here also. A striking phenomenon, for example, is the immediate violent reaction of potassium with bromine, while sodium, which is chemically so closely related to potassium, can be kept in contact with bromine for years.

²⁾ N. B. Pilling and R. E. Bedworth, *J. Inst. Metals*, **29**, 529, 1923.

³⁾ The phenomenon recalls the "craquelé" of the pottery maker's art, in which two layers of coloured glaze are applied one over the other to the object. The upper layer shrinks more than the other upon cooling, and thus exhibits numerous tiny cracks through which the colour of the underlayer becomes visible.

The volume of potassium bromide is smaller than that of potassium, the volume of sodium bromide is greater than that of sodium.

From the above a further condition which a metal must satisfy in order to be considered as a getter follows directly. No dense protective layers must be formed on the metal, so that the taking up of gas from the surrounding atmosphere can continue uninterrupted. This requirement is particularly important in connection with the metal oxide, since oxygen is one of the most dangerous contaminations in high-vacuum tubes, and a dense layer of oxide prevents the corrosion by other gases. In agreement with the rule of Pilling and Bedworth, therefore, getters must be sought among the metals whose oxide has a smaller volume than the metal. The alkali metals and the alkaline earth metals belong to this group. The former cannot usually be used since getters for radio valves and X-ray tubes must have a fairly high melting point in connection with the conditions of operation and manufacture. Moreover, the vapour tension of the alkali metals (except lithium) is too high. The choice is limited therefore to the alkaline earth metals, which are in fact commonly used as getters. Since the chemical activity of the alkaline earth metals increases in the order: magnesium, calcium, strontium, barium, it is clear that barium is especially suitable as getter.

Before continuing with the subject of getters we should like to complete the above discussion by contrasting them with the corrosion resistant metals.

Conditions for corrosion-resistance

Corrosion resistance can evidently be expected in the cases of the metals upon which dense coherent layers are formed by the action of gases (in addition to the precious metals such as gold, etc.). Since the protective action of such a layer is based upon the fact that the reacting substances are forced to diffuse through the coherent layer, the resistance to corrosion is greater, the lower the velocity of diffusion through the layer. This property must therefore be considered more closely.

As a matter of fact it is remarkable that diffusion takes place at all. Diffusion of course requires a concentration gradient, which means that the metal and gas atoms in the compound forming the surface layer must be present in variable proportions, thus in general in proportions which deviate from the exact stoichiometric composition. Such deviations are indeed possible. Most chemical compounds have a certain range in the system of their components (homogeneity range) within which the atomic proportions can change continuously without a new phase being formed. The excess of one of the components compared with the stoichiometric amount is then, as it were, in solid solution in the compound. If it is a question of a binary compound of the form AB , which contains an excess of the component B , this deviation from the stoichiometric composition may occur in three different ways

which are represented diagrammatically in *fig. 1*. In the compounds in question, of a metal and a non-metal, the components *A* and *B* are usually present in the form of oppositely charged ions. In this case, due to the strong repulsion between similar particles, only types *I* and *II* of *fig. 1* need be considered:

I) the points of the lattice *AB* are all occupied and the excess of particles *B* present are situated between these points;

II) part of the particles *A* are missing from the lattice *AB*, so that holes of atomic dimensions are formed.

In the first type diffusion takes place by the particles *B*

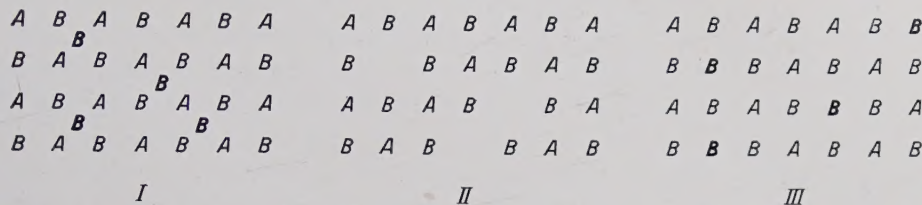


Fig. 1. When a compound *AB* contains an excess of the component *B* in solid solution there are three possibilities:

I) The excess particles *B* are situated at random spots between the points of the normal lattice *AB*.

II) In the lattice *AB*, there are here and there unoccupied points where *A* particles are missing from the stoichiometric composition.

III) In the lattice *AB* *A* particles are here and there replaced by *B* particles. (The representation is borrowed from C. Wagner and W. Schottky, *Z. phys. Chem. B* **11**, 163, 1930).

jumping from one intermediate lattice position to the one next to it, and thus moving from regions with large excess of *B* to regions with small excess of *B*. In the second type particles *A* can jump from hole to hole, and in this way diffuse through the layer. The last method of diffusion always takes place relatively rapidly, so that it is more favourable for corrosion resistance when the metal-gas compound can only have lattice defects of type *I*. Furthermore, the diffusion velocity under otherwise similar conditions is greater, the greater the possible difference in concentration of the excess particles *B* in the layer. Therefore it is desirable that the compound *AB* should have only a very small homogeneity range.

It may be mentioned in passing that type *I* usually occurs when the soluble component *B* present in excess is the metal; type *II*, when *A* is the metal. This is simply because the (positive) metal ions are usually considerably smaller than the (negative) non-metallic ions, and can therefore fit more easily into the spaces between the normally occupied lattice points. From this it may be seen that in both the diffusion mechanisms described the metal is the component which diffuses through the layer. This may seem strange since one is inclined to assume that if anything is to penetrate through the surface layer it ought to be the gas. In the cases investigated until now (the investigations have extended over the last ten years), however, it has been found that the metal actually diffuses through the metal-gas compound to the outside. If, for example, a copper wire is oxidized through and through at a suitable pressure and temperature, it is found to have become hollow. Another very convincing proof is the corrosion of silver by sulphur described by Wagner, which is illustrated in *fig. 2* and explained in the text beneath the figure. An explanation of the fact that it is always the metal which diffuses (thus in a lattice of type *I* particles *B*, in type *II* particles *A*), is furnished by the assumption that the

diffusing particles are ions, while electrical neutrality is maintained during the diffusion by the diffusion of a corresponding number of electrons. The positive metal ions, due to their small size, are much more mobile than the negative ions. By a consideration of the contributions made by the motion through the lattice of ions and electrons, respectively, to the total electrical conductivity of the metal-gas compound, this theoretical representation could also be confirmed quantitatively⁴).

In addition to the conditions mentioned for high corrosion resistance — homogeneity range of the metal-gas compound small and involving an excess of the metal — which follow

from the requirement of a low velocity of diffusion, and which therefore must also be manifested, according to the above, in a very low ionic or electronic conductivity of the compound, there are other more or less obvious requirements. The compound must have only a low vapour tension and must possess great hardness so that the protecting layer will not be volatilized or easily broken through upon mechanical injury. It is indeed found that the oxides of the metals commonly used in corrosion-resistant alloys, such as chromium and aluminium, are distinguished by just these properties.

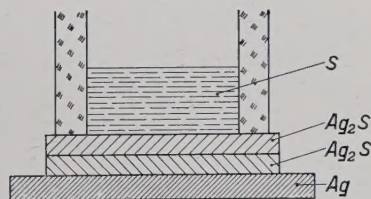


Fig. 2. A silver plate and two plates of pressed silver sulphide (Ag_2S) are pressed together, while at 220°C liquid sulphur is allowed to act upon the uppermost Ag_2S plate. A silver sulphide growth is seen to be formed upon this plate which becomes heavier, while the silver plate is found to decrease in weight correspondingly. The middle plate of Ag_2S does not change its weight. Therefore silver diffuses through the silver sulphide to the sulphur. (C. Wagner, *Z. phys. Chem. B* **21**, 25, 1933).

The solution of gases in metals. Zirconium as a getter

While the above discussion of the "getting" of

⁴) C. Wagner, *Z. phys. Chem.*, **B** **21**, 25, 1933; **32**, 447, 1936; **40**, 455, 1938.

gases will have made it clear why barium is a suitable getter, the same cannot be said of the second metal mentioned in the introduction, zirconium. Zirconium oxide has a greater volume than the metal — the condition for the formation of a protective oxide layer — and it otherwise satisfies practically all the requirements which have just been mentioned for a corrosion-resistant metal. Below 200°C zirconium is indeed one of the best corrosion-resistant metals. At high temperature, however, a new phenomenon appears, which in our discussion has not yet been taken into account: the oxide is dissolved in the zirconium.

This effect could be neglected in the foregoing since the solubility of, for instance, oxygen or nitrogen in most metals is very small. Up until quite recently the greatest of such solubilities known were those of oxygen in silver and of nitrogen in iron; in both cases the solubility at room temperature is less than 0.01 atoms per cent. In recent years, however, it could be shown⁵⁾ that there are several metals which can take up many atoms per cent of oxygen and nitrogen in solid solution, and that this is especially so with zirconium. In this case also the phenomena have been studied in the greatest detail. Oxygen particularly is extremely soluble in zirconium. Even a sample with the composition 60 at. % Zr + 40 at. % O was found by X-ray analysis to form only one phase (with a hexagonal lattice). For nitrogen the limit of solubility lies at about 20 atoms per cent of N.

The taking up of oxygen or nitrogen atoms in the zirconium lattice (which is found to take place in the interstices of the lattice) may occur directly from the gas phase or from a layer of zirconium oxide or nitride which has been formed on the surface of the metal. In order that the layer should rapidly disappear completely, the great solubility is, however, not sufficient; the atoms taken up must also be able to diffuse easily from the outside to the inside of the zirconium lattice, in order to make room for new ones. This velocity of diffusion is found to be extremely small at low temperatures⁶⁾. This is the reason why the oxide or nitride layer on zirconium remains intact and protects the metal from further "corrosion". At higher temperatures, on the other hand, above 1000°C , for instance, the oxygen and nitrogen atoms (or ions)

diffuse very easily through the zirconium lattice, so that homogeneous solutions are obtained and the metal surface is continually restored as long as the limit of solubility is not reached.

In order that, in spite of their great mobility in the metal lattice, the oxygen and nitrogen atoms shall not leave it, the energy level of the gas in the metal must lie considerably lower than outside the metal, *i.e.* the gas must be held bound in the metal by strong chemical forces. This is actually the case in zirconium. If the other metals related to zirconium in the fourth main group of the periodic system of the elements are examined, it is found that the chemical activity increases in the order: titanium, zirconium, hafnium, thorium. Just as in the case of the alkaline earth metals one would expect to find the best getter qualities in the last metal of this series. It has, however, been found that the unusually high solvent capacity occurs only in the case of the first three. Since hafnium is very expensive and differs in properties only slightly from zirconium, zirconium has been chosen from this group for use as a getter.

In addition to oxygen and nitrogen, other gases also, especially hydrogen, are taken up in large quantities by zirconium in solid solution. While for the taking up of all other gases the most favourable temperature of the zirconium is the highest possible, this is not so with hydrogen. For this gas there is a definite, optimum temperature zone between 300 and 400°C . In order to understand this we must observe the process of solution from a different angle for a moment.

At a definite constant temperature T_1 the amount of gas c , which a metal can contain in solid solution, at first increases with the pressure p of the gas in

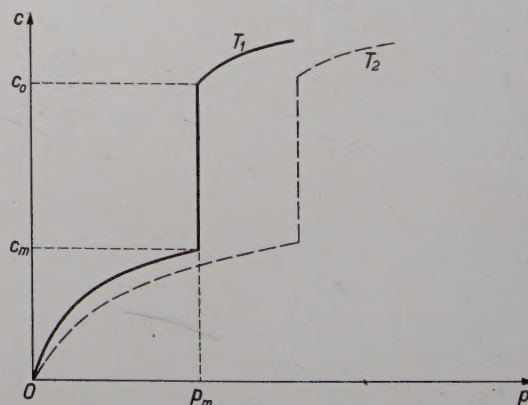


Fig. 3. The amount of gas c dissolved in a metal at constant temperature T_1 at first increases with the pressure p . At the limit of solubility c_m the equilibrium pressure of the solution is p_m . Then, while the pressure remains constant, a metal-gas compound begins to be formed. When all the metal is converted into this new phase (amount of gas taken up c_0), upon further increase in pressure the gas content in the compound can in general still increase (range of homogeneity).

⁵⁾ J. H. de Boer and J. D. Fast, *Rec. trav. chim. Pays Bas* 55, 459, 1936; J. D. Fast, *Metallwirtschaft*, 17, 641, 1938.

⁶⁾ Actually it is not a question of the diffusion alone, but also of the passing of the atoms of the gas through the boundary surface of the metal, for which, as for diffusion, a certain activation energy is necessary.

the surrounding atmosphere, usually ⁷⁾ proportionally with \sqrt{p} (see fig. 3). At a certain pressure p_m the limit of solubility c_m is reached, *i.e.* the gas no longer dissolves, but in addition to the metallic phase a new phase (a metal-gas compound) begins to be formed, and the pressure remains constant until all the metal has been converted into the metal-gas compound. At a higher temperature T_2 the equilibrium pressures in the cases in question are higher for all values of c . With a given solution, therefore, the amount of gas dissolved can be decreased not only by decreasing the gas pressure at constant temperature, but also by increasing the temperature at constant pressure.

As an example let us consider the solution of oxygen in silver. At a temperature of 200° C a limit of solubility is found of 0.016 at. % at a pressure $p_m = 1.74$ atm. For 500° C the corresponding values are 0.17 at. % and $p_m = 386$ atm. Since these pressures can easily be realized experimentally, it is thus possible to cause the oxygen content of silver to increase or decrease at will within the limit of solubility. In the case of the solution of oxygen and nitrogen in zirconium, on the other hand, the values p_m and, *a fortiori*, the equilibrium pressures, at gas contents below the solubility limit, are found to be so small ($<10^{-6}$ mm Hg) that they cannot be attained even with the best high-vacuum pumps, and this is even true at temperatures of for instance 1500° C. From this it follows, on the one hand, that upon employment of a sufficient amount of zirconium as getter in oxygen or nitrogen, the gases will be taken up except for infinitesimally small amounts, and on the other hand, that afterwards the gases once taken up cannot be driven out of the zirconium with all the existing means at our disposal!

It will now be clear that it was unnecessary to speak of equilibrium pressures of the solid solution when discussing the action of zirconium as a getter for oxygen and nitrogen. In the case of hydrogen, however, the equilibrium pressures of the solution in zirconium can only be neglected at low temperatures. At temperatures above about 400° C they may already lie higher than the pressures which are considered permissible in high-vacuum tubes. The hydrogen taken up at a lower temperature from the evacuated tube would then be partially given off again. On the other hand, with increasing temperature, just as in the case of oxygen and nitrogen, the velocity with which hydrogen is taken up by the

zirconium becomes steadily greater. The most favourable compromise seems to lie in the temperature range mentioned, 300—400° C.

The method of application of barium and zirconium as getters

Thanks to the property that at room temperature zirconium does not act as a getter, because of the oxide and nitride layers formed (on the contrary it is particularly corrosion-resistant), no special measures need be taken while introducing zirconium into the high-vacuum tube. Barium, however, which also acts as a getter at lower temperatures, and which is therefore very unstable in air, must be protected by, for instance, enclosing it in a jacket of copper or nickel when it is introduced into the tube. After the tube has been evacuated to a certain pressure, the barium is freed in vapour form by heating, and condenses as a mirror on the glass wall of the tube. Upon evaporation the barium already takes up greedily any gas left in the tube, so that the tube is evacuated much more quickly to a lower final pressure than is possible with a pump. This action is also obtained with magnesium (the least active of the alkaline earth metals), and magnesium was formerly used for this purpose on a large scale; since, however, magnesium when in the solid state takes up practically no more gases, it does not entirely fulfil the function of a getter as outlined in the introduction.

In certain cases the manner of introducing the barium encounters the objection that the metal may also condense on spots, where its presence is undesired. Moreover, the presence of the metallic mirror has an unfavourable influence on the heat radiation through the glass, which is serious especially in certain types of transmitting valves. These objections are avoided by using zirconium. This metal can be applied as a thin layer on one of the electrodes or support wires or it may be in the form of a separate rod or plate in the tube. Care must only be taken that part of the zirconium remains at a relatively low temperature (400° C for instance) during operation, in order to bind the hydrogen, while another part must assume much higher temperatures in order to take up the oxygen, nitrogen, etc. rapidly. At the same time the spot where the getter is applied must be chosen so that it can easily be reached by the gas atoms freed at another spot which are to be bound. This latter action can be very much promoted by bringing the getter to an electric potential such that any gaseous ions formed will be drawn towards it.

⁷⁾ Namely, when the molecules in the gas phase consist of two atoms and the gas dissolves in the metal phase in atomic form.

A NEW FITTING FOR ROAD LIGHTING

by J. BERGMANS and W. L. VERVEST.

683.854: 628.971.6

The advantages of mirror reflectors for road lighting are only fully enjoyed when an attempt is made to make the distribution of brightness over the surface of the road as uniform as possible for all conditions of the road surface (dry, damp, wet). It is known that uniform illumination is not necessary, and even undesired for this purpose. An examination is made of a new light distribution in which not only the reflecting properties of the dry roadsurface are considered but also those of a damp or wet surface. It is also shown that this new light-distribution of the road lighting fitting is also more satisfactory as far as glare is concerned than the light-distribution which corresponds to a uniform brightness on a dry road only. A description is given of the fitting ZE 30 developed on this basis, which is not only suitable for mounting on poles but also for suspension on cross wires. In conclusion photographs and visibility measurements of an installed system are given.

Introduction

In the lighting of roads and highways the aim is to provide sufficient brightness for the eye of the roaduser on a long narrow strip, with a relatively small number of light points. In order to prevent wastage of luminous flux in the strips of ground lying beside the road or on the house fronts, it is logical to choose the light distribution of the light source in such a way that the luminous flux is directed mainly on to the surface of the road. This is more important the higher the light sources are mounted, according to the tendency of modern road lighting. Mirror reflectors and other fittings for directed light, by means of which the light distribution can be very considerably influenced, will therefore be more suitable for the purpose than fittings with diffusely transmitting or reflecting surfaces where the light distribution is less under control, so that when, for instance, the light sources are high it is impossible to prevent the house fronts from being disturbingly brightly illuminated.

One may therefore reasonably expect that for road lighting the best solution is a fitting with specular reflection. Nevertheless, in practice objections have been encountered to the use of mirrors or refractors, namely the following:

1. On damp and wet pavements a poor distribution of brightness was obtained.
2. The reflectors caused more glare.
3. The illumination on both sides of the street, for instance that of the house fronts, was often insufficient.

In the following it will be shown that these objections are not fundamental to mirror reflectors, but that in the design of the most appropriate light distribution the reflecting properties of damp or wet road surfaces are not duly taken into account.

Brightness distribution on the road surface

It has long been known, and it has been confirmed by recent investigations ¹⁾ that for good observation on the road it is advisable to make the distribution of brightness as uniform as possible. In order to obtain this uniform distribution of brightness a uniform distribution of the illumination is, however, by no means the prevailing condition. This may be expressed in another way by remarking that the light distribution of the fitting must be corrected for the reflecting properties of the road surface. We have, however, found in publications only examples for this correction with dry roads and we emphasize that, as far as we know, these corrections for wet roads-surfaces are wanting.

To give an impression of the difference in brightness distribution, which happens to occur, when a definite installation changes over from dry to damp, we mention that certain points of the road surface will get a brightness 10 to 20 times higher and other points 3 times lower.

It is therefore clear that after correcting the fitting for a dry road surface large differences in brightness will occur, if the roadsurfaces is damp or wet.

We shall see, that if in computing the light distribution the reflecting properties of the damp road surface are also taken into account lighting installations can be made with give perfect results under all weathering conditions.

Glare with fittings using specular reflecting or refracting surfaces.

In the observation of the relatively low bright-

¹⁾ See P. J. Bouma. Measurements carried out on road lighting systems already installed, Philips techn. Rev. 4, 292, 1939; Peri, Rilievi sperimentali sulla illuminazione di strade. Communication to the 43rd annual meeting of the A.E.I. in Turin, Sept. 1939.

²⁾ This is dealt with in more detail on page 98 of J. Bergmans: Light reflection by road surfaces, dissertation, Delft 1938.

nesses on the road, the sensitivity of the eye to contrast plays an important part. The glaring effect of a light source can therefore best be judged by determining the decrease in sensitivity to contrast which results from the glare. As has already been discussed in this periodical³⁾, this glare depends in the first place upon the illumination on the eye by the glaring light source, and upon the angle between the direction of incidence of the disturbing light and the direction of view.

When in practice it has been observed that a mirror reflector gives rise to more glare than a diffusing fitting, the cause must be sought in the greater illumination received by the eye, in the case of the mirror, from a direction which makes only a small angle with the direction in which the objects were observed.

If in designing the light distribution of a fitting not only the reflecting properties of the dry road surface are considered but also the properties of the surface being damp, a smaller amount light will be radiated in directions making small angles with the direction of view. This results in light distributions, which are much more satisfactory from the point of view of glare. In order to demonstrate this we must, however, first consider more closely the reflective properties of ordinary road surfaces.

Brightness coefficients of the average road surface

As has already been explained in this periodical⁴⁾ the reflective properties of a road surface can be represented with the help of the so-called brightness coefficient q . By the brightness coefficient is meant the ratio for a given point, of the observed brightness and the illumination, which is a function of the direction of illumination and of vision.

The value of q for a given point is determined not only by this combination of directions, it is also dependent on the nature of the road surface, and moreover, it changes very much with the degree of moisture on the surface. It therefore seems very doubtful at first glance whether it is possible, by measurements of the brightness coefficient under different circumstances, to arrive at a kind of average reflection characteristic of a road surface, which could form the basis for the calculation of a lighting fitting of general utility, and thus not based upon a special road surface and a certain state of moisture on that surface.

In practice, however, this is actually found to be possible. If for one definite combination of direc-

tions of illumination and observation the individual values of q are measured for different types of road surface, it is found that in the dry state they differ by a factor 4 and in the damp⁵⁾ state by a factor 9. If now for a given combination of directions we determine the geometric average of these values of q , then the individual q values will only deviate by a factor of 2 from the average in the dry state. In the same way we determine the geometric average for the damp state. In this case the individual q values will only deviate by a factor 3 from that average. By this process one thus obtains two sets of q values, which are representative of the average dry road surface and the average damp road surface.

The factors 2 and 3 between the brightness coefficients of various road surfaces with the same combination of directions are small compared with the ratios between the brightness coefficients which may occur for the same road surface for different combinations of directions of illumination and observation, which are of the order of 1000. We may therefore say that the brightness coefficient changes mainly with the direction of illumination and observation, and only to a lesser degree with the nature of the road surface, so that the introduction of the above-mentioned average road surface is justifiable.

Fig. 1a and b give a diagram of the reflective properties of the average road surface just introduced. We assume that the road is lighted from a point 10 m vertically above L , and that the observer (height of eye 1.5 m) stands at A , 150 m from L . For each point on the road surface the combination of direction of illumination and observation is then determined, so that we can note the corresponding q values calculated as the geometric average of our measurements on different road surfaces. The curves of fig. 1a connect points with the same value of q in the dry state and fig. 1b gives similar "iso- q " curves for the damp state of the average road surface. Both states of the surface differ very much in the nature of their reflection from completely diffusely reflecting surfaces; a much stronger reflection occurs in certain directions. The average reflection coefficient of very bright road surfaces⁶⁾ is a maximum of about

³⁾ See P. J. Bouma, The problem of glare in highway lighting, Philips techn. Rev. 1, 225, 1936.

⁴⁾ J. Bergmans, The brightness of road surfaces under artificial illumination. Philips techn. Rev. 3, 313, 1938.

⁵⁾ More detailed specification of the damp but not yet inundated state was given in the author's dissertation (see footnote²⁾ on pages 81 and 82. See also the first article cited in footnote¹⁾.

⁶⁾ The highest diffuse reflection coefficient which was measured in an elaborate investigation of about 40 different road surfaces was 29 per cent. See in this connection and in connection with the definition of the "average" reflection coefficient, the article cited in footnote¹⁾ pages 296 and 297.

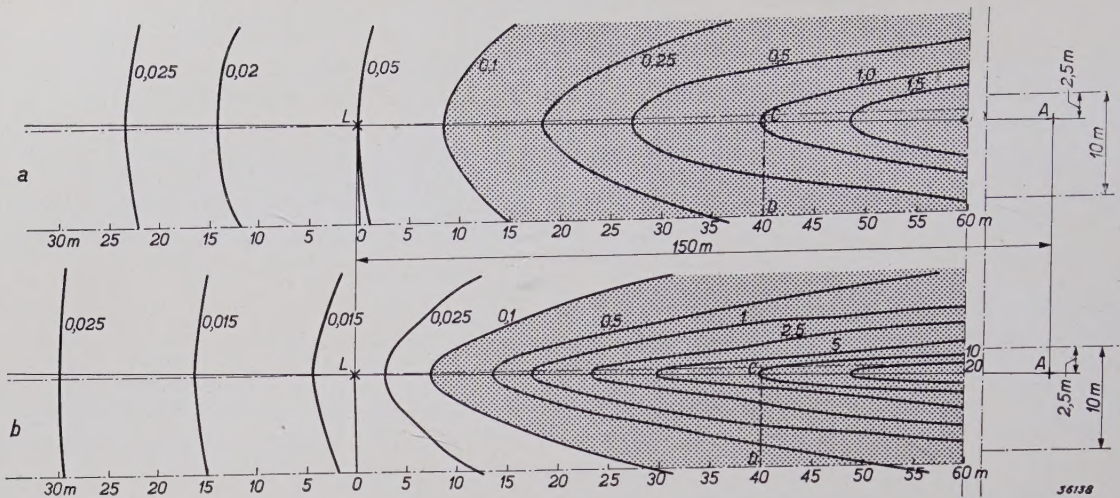


Fig. 1. A road 10 m wide is illuminated by a light source suspended 10 m above L on the curb. At a distance of 150 m from L the observer A stands 2.5 m from the curb above which the source hangs. For an average road surface lines are drawn through points with the same brightness coefficient expressed in c.p./m² brightness per lux illumination; a) for the dry state, b) for the damp state of the road surface.

$q = 30$ per cent. If we assume a completely diffuse reflection, in which of course $q = \text{constant}$, then this would correspond to a q value of 0.1, because

$$q = \frac{B}{E} = \frac{\rho E/\pi}{E} = \frac{1}{\pi} \rho = \frac{0,3}{3,14} \approx 0,1.$$

The part of the road where the brightness coefficients of the average road surface are actually higher than 0.1 is shaded in fig. 1a and b. It may be seen that this is the case on a very large part of the road surface. In the case of the average dry road (fig. 1a) local regions occur with a q value 15 times as high, while the damp road (fig. 1b) exhibits q values at certain places more than 200 times as high. There are, however, also places (on the non-shaded part of fig. 1a and b) where the value of q both in the damp and the dry state is about five times as small as with the diffuse comparison surface.

From this comparison it may therefore be seen how extremely important it is in the construction of fittings to take into account the actual reflection properties of the road surfaces.

Chosen distribution of the luminous flux over the road surface

As indicated above, in order to obtain the best results as to visibility the fitting must provide a light distribution such that the brightness of the road surface is as uniform as possible. The q values may serve as a guide. By definition q is the quotient of brightness and illumination, so that in order to attain uniform brightness the illumination at every point of the road surface must be inversely proportional to the value of q .

Since a road lighting fitting must be able to be

used not only when the road is dry but also when it is damp, a compromise must be found between the light distributions which would follow from figs. 1a and b for the two conditions. In order to show how this is done we shall deal with a definite example. We assume that the light source is suspended vertically above the edge of the 10 m wide road (see fig. 1a and b), and we consider the transverse cross section CD which is 40 m, i.e. a distance equal to four times the suspension height of the light points, away from L . The variation of the brightness coefficient over this cross section, which can be read off in fig. 1a and b, is given separately in fig. 2 (q_d and q_v , respectively). It may be seen that the brightness coefficient of the point D , i.e.

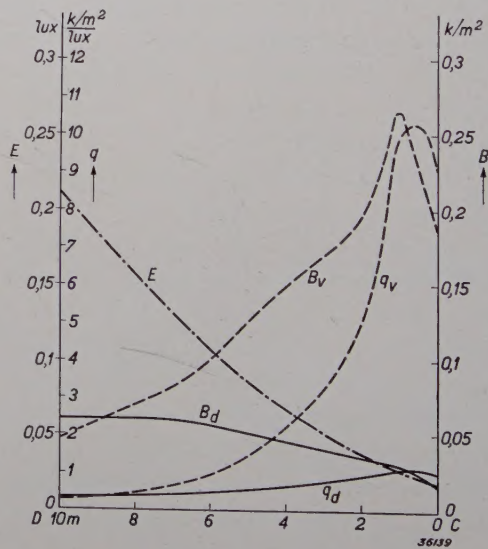


Fig. 2. Variation of the brightness coefficient q , the illumination E and the brightness B along the line CD of fig. 1 for a dry road surface (full lines) and for a damp surface (broken lines).

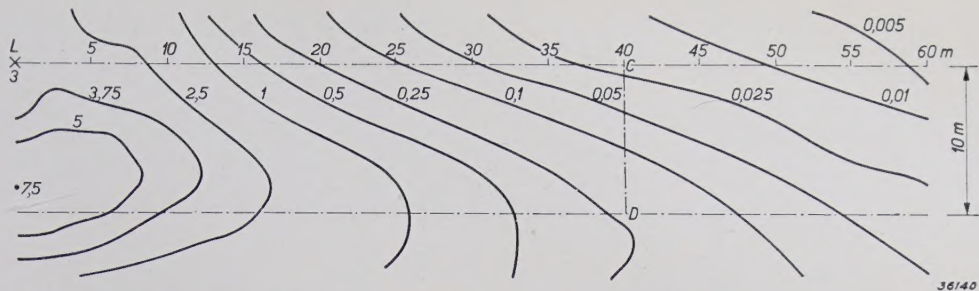


Fig. 3. A fitting of the type ZE 30 provided with a mercury lamp type 125 W MB/V is situated 10 m above point *L* on the edge of a 10 m wide road. With a total luminous flux of 5 000 lm of the lamp the values of the illumination given in lux are obtained on the pavement. Iso-lux curves are drawn on the surface of the road, from which it may be seen that the opposite side of the road is much more strongly illuminated than the side where the fitting hangs, cf. for example points *C* and *D* 40 m from the source.

on the opposite side of the road, for dry and damp states has practically the same value, namely about 0.3; at point *C*, on the same side of the road as the light source, the brightness coefficients for dry and damp states are very different, about 3 and 30 times as great as on the opposite side of the road, respectively.

If the points on the line *CD* are illuminated uniformly, which is approximately the case with most fittings now in use, curves *q_d* and *q_v* also give the variation of the brightness, and the brightness at *C* would exhibit a pronounced maximum. This is then manifested in the appearance of narrow, very bright streaks on the road surface which may be extremely disturbing for observation, since a small obstacle, a pedestrian or cyclist for example, standing next to such a streak is not observed at all.

From the foregoing, the remedy will be obvious: the light must be emitted chiefly toward the opposite side of the road, so that the illumina-

tion of point *D* is greater than at *C* by a factor 10. The effect of the greater brightness coefficient at *C* is then compensated in the most satisfactory way. With a dry road surface the brightness at *D* is then about 3 times as great, and with a damp surface about 3 times as small as at *C*, and these are brightness differences which may be considered permissible. We are thus faced with the remarkable fact that the brightness which is caused on the opposite side of the road in the dry state is greater than the brightness on the side where the light source itself stands.

The practical realization of this conception has led to the construction of a new fitting equipped with specular reflecting surfaces which will be described in the following.

Fig. 3 gives the distribution of the illumination over the road surface when the new fitting is used, and shows that the illumination on the opposite side of the road is indeed many times as

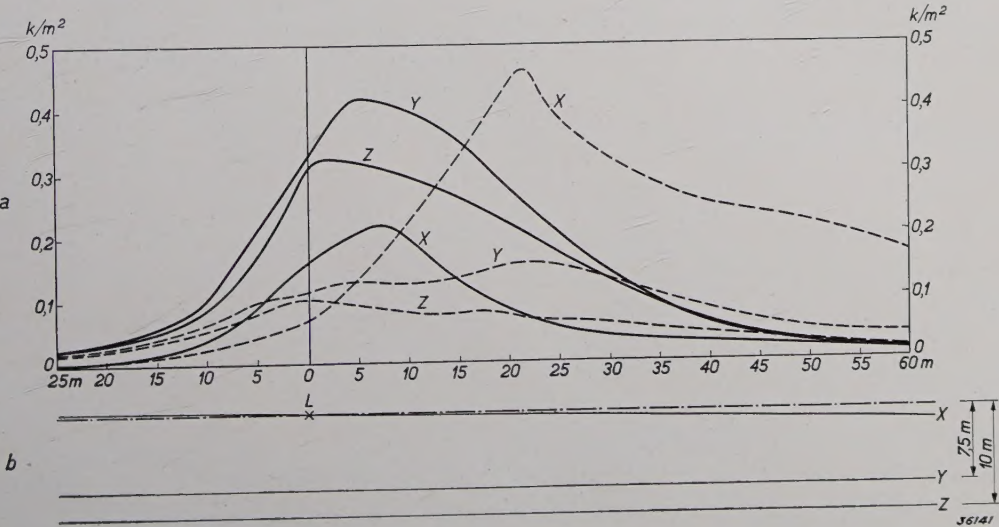


Fig. 4. Variation of the brightness (*a*) on the road along three different lines *x*, *y* and *z* which are indicated in (*b*). Line *x* is the line joining *L* with the observer *A*. Line *z* is the opposite edge of the road and *y* is parallel to it and 2.5 m away from it; *y* is thus the centre line of the opposite traffic lane. The full-line curves refer to the dry state, the broken-line curves give the variation of brightness for the damp state.

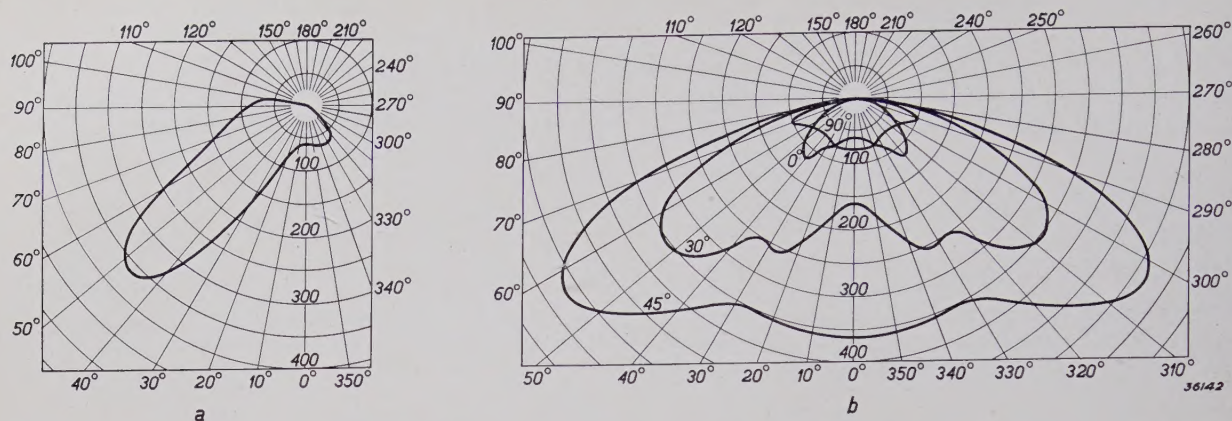


Fig. 5. Distribution of luminous intensity with the fitting type ZE 30 provided with a mercury lamp type 125 W MB/V.
 a) Distribution in the vertical plane perpendicular to the axis of the street.
 b) Light distribution in four planes indicated in fig. 6.

great as on the side where the source of light hangs.

In fig. 4a it is shown how the brightness on the street varies along three different lines x , y and z , specified in fig. 4b. Line x is the line joining L with the observer A . Line z is the edge of the road on the opposite side, and y is parallel to it and 2.5 m from it, i.e. it marks the middle of the opposite traffic lane. The full-line curves in fig. 4a refer to the dry state, while the broken-line curves give the variation of brightness for the damp state of the road surface.

It may be seen from these curves that the remarkable effect which was described above for the transverse cross section CD , holds not only for that particular place, but that for a whole strip of the roadway the brightness in the dry state on the opposite side of the road is higher than on the side where the light sources are suspended. In this way the bright streak on the road surface is made as broad as is practically possible.

Distribution of the luminous intensity of the new fitting

The light distribution which has been given to the new fitting ZE 30 may be seen in fig. 5. The light distribution of a fitting is ordinarily given by drawing the polar light distribution curve for several vertical planes passing through the source. When the light distribution in these planes varies only slightly, there is not much objection to this method. With a fitting which has a very unsymmetrical light distribution, such as the one here described, great difficulties are however encountered, because the points of the road surface for which the illumination can then be calculated, are distributed very unevenly over the roadway. We have

therefore chosen a different method of representation, in addition to the polar light distribution curve of the plane perpendicular to the direction of traffic and we have measured similar curves (see fig. 5a) and drawn them for planes which are derived from the vertical plane parallel to the direction of the road by rotating it about a horizontal line passing through the light source (see the curves of fig. 5b and the indication of the measuring planes in fig. 6). When these curves are used, then the points for which the illumination on the road can be computed are distributed much more logically over the surface, while from such a representation, the question, which is for instance important in the problem of glare, can be answered as to how the candle-power varies for an observer moving normally along the road, i.e. along the direction of the length of the road.

It is striking how little light is emitted by the fitting in the vertical plane (0°) parallel to the axis of the road. Especially at small angles with the horizontal a very limited luminous intensity in this plane, due to the high value of q , gives the best results for attaining the correct brightness distribution over the road surface.

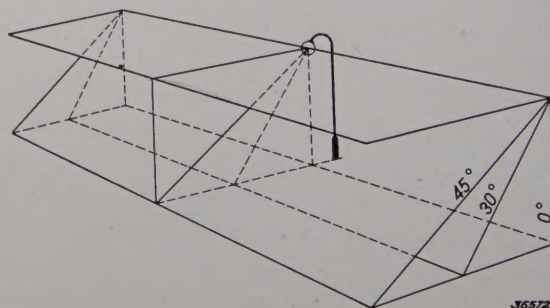


Fig. 6. Sketch in perspective of the planes for which the light distributions in fig. 5 are drawn.

Due to the low candle power in this direction the disturbance by the light from the source is also a minimum. The two requirements of the greatest possible uniformity of brightness, also in the damp state, and that of low glare are therefore not mutually exclusive, but on the contrary can be realized at the same time.

An important point to which attention must still be called is that the luminous intensity in each of the curves of *fig. 5b* passes very gradually from the highest value to the very small value in the horizontal direction. The nature of this transition is of great significance for the distribution of brightness in the perspective of the road. When instead of the curve chosen by us, there was a sharp cut off at 70 or 80°, as often occurs with other fittings, then this cutting off would be manifested on the road surface as an annoying stripe. As may be seen in *fig. 1a* and *b* especially in the damp state, the brightness coefficient on the line joining *L* and *A* increases very sharply with increasing distance from *L* when the distance from *L* is greater than the distance corresponding to an angle of emission of 70°. This results in the fact that with many fittings the brightest spot in the damp state lies at a point on the above-mentioned line between 70 and 80°. If all light radiation is suddenly cut off at greater angles, a very disturbing brightness distribution occurs on the road surface. With the very gradual cutting off which is shown in the curves of *fig. 5b*, this phenomenon need not be feared.

Finally we wish to call attention to the radiation in the horizontal plane (90°). The light emitted in this direction is not incident on the road itself, but illuminates the houses standing on the road, so that the road is not as it were isolated, and police patrol service is made easier. From the nature of the case the illumination of the house fronts may and must be lower than that of the road. Too low an illumination, however, may be detrimental to the safety of those who leave a house and enter the road, since they are not promptly observed by the traffic on the road. If the house fronts are illuminated with light sources which are all mounted on the same side of the road, a much too local illumination of a few houses is obtained, while the others remain too dark. If this is prevented by specially directing the light toward the more distant houses, the latter cause disturbing shadows so that the desired effect is not reached. By illuminating the house fronts from the opposite side, on the other hand, good results can be obtained.

Position of the fitting with respect to the surface of the road

In *figs. 1a, 1b* and *3* we have indicated the edges of the road with dash-dot lines in such a way that the light source was situated just above the edges. This does not mean, however, that the fitting could not be used satisfactorily suspended on wires over broad roads. In this case also care must be taken for as uniform possible brightness over as broad as possible strips of the road surface, and for this special purpose the new fitting is suitably constructed. In order to illuminate the house fronts also, the fittings must be so hung that they always radiate from the outside of the road towards the middle.

In order that the fitting shall be in the proper position with respect to the surface of the road, it must if necessary be fastened to the suspension wire by means of a flexible line coupling device (*fig. 7*).

Due to the twisting of the suspension wire a small amount of swing about a horizontal axis perpendicular to the direction of the traffic will be retained. Such a swing, which is unusually annoying in fittings with a sharp cut-off, is undisturbing in the case of the new fitting due to the "gradual cut-off" of the light.

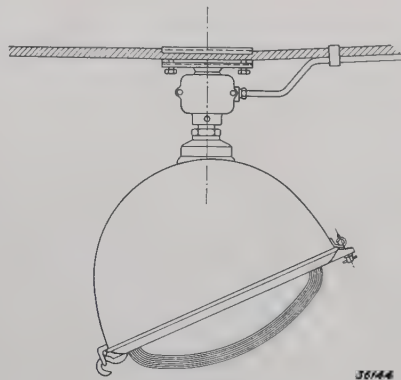


Fig. 7. The fitting can be fastened with a clamp arrangement so firmly to the suspension wire that it can only swing about a horizontal axis perpendicular to the direction of the street. The swinging about this axis, namely about the suspension wire, which occurs in windy weather, is not disturbing.

Construction of the new fitting

Care has been taken in the construction that the glass parts, mirror and cover, each in its frame, can be easily introduced into the housing when it is assembled, and that at the same time they can be removed from the fitting in a simple manner in order to be cleaned. In both cases the system has been used with a hook on one side and a screw for fastening on the other (see *fig. 8*). Not only the screw which holds the mirror fast (at *C*),

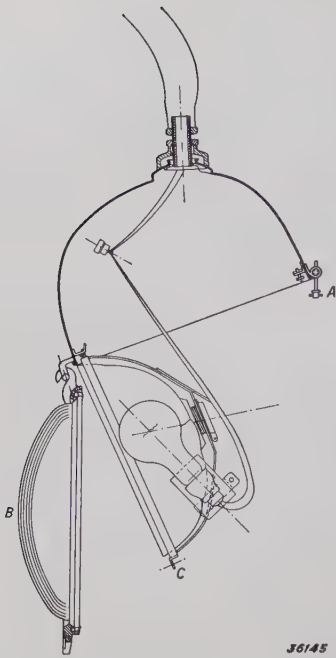


Fig. 8. Fitting ZE 30 shown opened. The cover glass and the mirror, both fastened in their steel frames are hooked on at one side. The fitting is closed by screwing tight the frame of the cover glass at the other side.

but also the nut *A* with which the cover glass *B* is fastened, cannot be lost, and are so constructed that if they are loosened by vibration, the parts are still held together.

In *fig. 9* a diagram is given of the paths of the rays in the reflector. Mercury lamps as well as ordinary incandescent lamps may be used. In order to obtain about the same light distribution in both cases it was necessary to choose a different position for the mercury lamps. (75 W or 125 W MB/V) from that for the ordinary incandescent lamps. In *fig. 9* the position of the incandescent lamps is indicated

by *G* and that of the mercury lamps by *K*. This is carried out technically so that there are two spring clamps (*fig. 8*) in the frame of the mirror for holding the cylinder in which the lamp holder is fastened. One spring clamp serves for the incandescent lamp and the other for the mercury lamp. It is also indicated on the fitting cylinder at what height each lamp must be set in order to obtain the desired result.

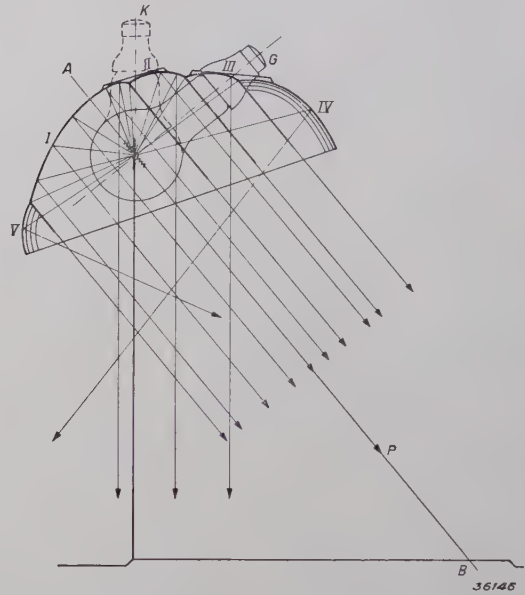
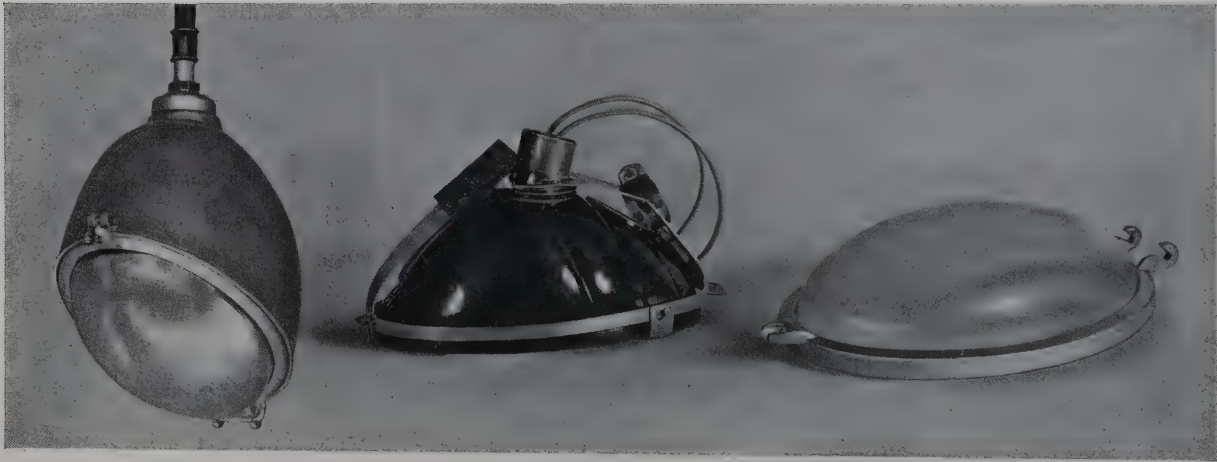


Fig. 9. The silvered glass mirror of the fitting ZE 30 consists of segments *I-V*. The largest part of the light is reflected in the direction *APB*. The correct position of the electric lamps with respect to the mirror is indicated by *G*, that of the mercury lamps 75 W or 125 W MB/V by *K*.

Fig. 10 is a photograph of the fitting and of each of the main components: housing, mirror frame and covering glass. In the photograph of the mirror



a) Fitting ZE 30 suspended ready for operation (height of the complete fitting about 40 cm);
b) mirror frame;
c) cover glass.



Fig. 11. Road provided with ZE 30 fittings in which are mercury lamps 125 W MB/V (5000 lm). Height of suspension of the light sources 9 m, spacing 34 m. All the sources are on the same side of the street above the curb. Width of street curb to curb 12 m. Dry road surface. Above is a series of density standards for the determination of the brightness of every point on the road surface; see the article cited in footnote ¹).

frame it may be seen that the mirror is made fast by means of a large coiled spring and that no screws are used for this purpose.

The silvered glass mirror is provided with a special protecting layer of fired enamel. The silver layer is thus situated between two glasslike surfaces, in front the glass body of the mirror and on the back the layer of enamel. This provides sufficient protection of the silver layer not only against effects of temperature, but also against those of the atmosphere. Such mirrors are also resistant to the effects of sea air, so that the fitting can be used without danger close to the sea.

In *figs. 11 and 12* two parts of a street are shown which is illuminated with the fitting ZE 30. The light sources are set up on only one side of the road. This arrangement, which is much less favourable than one on both sides or over the middle of the road, offers great advantages in judging the fitting. From a photograph it is impossible to see from which source of light a given spot on the road surface is illuminated. When, however, the light sources are only situated on one side of the road, and considerable brightness is observed in the photograph on the other side of the road, it is

certain that this is due to the good qualities of the fitting.

The road shown in *figs. 11 and 12* is 12 m wide from curb to curb. The light sources are suspended at a height of 9 m above one curb at intervals of 34 m. Mercury lamps type 125 W MB/V were used which give a luminous flux of 5 000 lumens. Power installed 3.8 kW per km. The road surface consists of granite blocks.

The photographs show clearly that even with this unfavourable ratio of width of road to height of suspension (12 m to 9 m) the entire surface of the road, damp as well as dry is sufficiently uniformly bright. The fronts of the houses on the opposite side of the road are also clearly visible.

For measurements of visibility a distinction must be made between the values which are observed when one stands on the half of the road upon which the light sources are situated and those on the other side. For the two cases, which correspond to the two directions of the traffic, we have determined the smallest observable contrast, namely at the most favourable spot (*Z*) and the least favourable spot (*z*) in the field of vision. These measurements were carried out in dry as well as damp weather.



Fig. 12. The same installation as in *fig. 11* with damp road surface.

The results are the following ⁷⁾:

		dry	damp
Observation on the side of the light sources	{ Z	31.9	39
	{ z	38.2	15
Observation on the opposite side	{ Z	30.4	34.2
	{ z	39.2	50

The above values for a road lighted on only one side of such a width and with such a low power installed, may be considered very satisfactory, and they show especially that the decrease in visibility upon transition from dry to damp is very slight.

⁶⁾ Similar measurements on numerous other road surfaces are discussed in the article cited in footnote ¹⁾.

AN ELECTRODYNAMIC PICK-UP FOR THE INVESTIGATION OF MECHANICAL VIBRATIONS

by J. SEVERS. 621.317.351 : 621-752

In the case of the Philips vibration pick-up GM 5520 the mechanical vibrations of the object investigated are converted electro-dynamically into an electrical alternating current voltage, whose variations can be made visible on the screen of a cathode ray oscillograph. The construction of the pick-up, particularly as concerns the choice of characteristic frequency, the damping and the sensitivity required, are here briefly discussed. The interpretation of the velocity and deviation oscillograms obtained, and the method for quantitative measurement of vibration are then dealt with. When the oscillograph GM 3 156 is used, the vibration to be investigated can be shown with an enlargement of 3500 times at frequencies down to 10 c/s. In conclusion a discussion is given of the way in which the pick-up can be applied to the vibrating object, and several examples of its use are dealt with.

In the last decades increasing attention has been devoted to the mechanical vibrations which occur at all kinds of spots on technical objects, and which may be undesired for various reasons. In the case of parts of engines or structural parts, for instance of motors, aeroplanes, bridges, etc. it is the destructive effect of the vibrations, in other cases, such as in ships, vehicles and buildings, it is the annoyance of the vibrations to human beings which makes it necessary to combat them.

Before they can be combatted they must be known. How are mechanical vibrations investigated? Various instruments have long existed for this purpose which enlarge mechanically or optically the generally very small deviations occurring upon vibration to values which can be read off directly or recorded if desired. A more modern method is to bring about the enlargement not mechanically or optically, but electrically. In this way, thanks to the highly developed amplifier technique, it is easily possible to investigate vibrations with relatively high frequencies and low ampli-

tudes, while at the same time the possibility is offered of constructing handy, transportable apparatus, which, unlike most of the older apparatus, is not confined to a given method of arrangement nor to a definite direction of the vibrations.

Use is made of these possibilities in the Philips vibration pick-up GM 5 520, which we shall describe in this article.

The method of converting the motion

The enlargement is obtained in the case of the electric vibration pick-up by converting the varying deviation of the vibrating object into a varying electrical voltage, which can then be amplified at will, and whose variations, made visible on the screen of a cathode ray oscillograph, form a picture of the variation of the deviation to be measured. In the Philips vibration pick-up the conversion of the mechanical vibrations into an A.C. voltage is carried out on the electrodynamic principle: a magnet whose lines of force cut the windings of a coil is allowed to follow the movements of the vibrating

object. It is obvious that it is here necessary that the coil should not follow the movements of the vibrating object, since only with a relative displacement of magnet and coil will a voltage be generated. This involves a fundamental problem which we shall first examine in more detail.

It is a very general rule that the deviation of a point on the vibrating object can never be measured except by the relative displacement of that point with respect to a second point whose motion is known. The simplest thing is to choose for the second point a fixed point which does not take part in the vibrational movement. This is, however, impossible in many cases. It is only necessary to think of the vibrations which occur during earthquakes: no fixed point outside the earth's surface is available, and points on the earth's crust which do not share in the vibration, or to only a small degree, are too far away to be used for the measurement. In the vibrations of ships, bridges, etc., and in general in the vibrations of large masses at low frequencies (several c/s), the same difficulty is usually encountered.

For such cases one may choose as point of comparison the position of a mass which is connected by means of a spring to the vibrating object (fig. 1). If m is the mass, c the stiffness of the

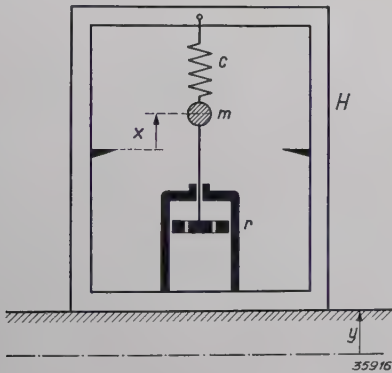


Fig. 1. Diagram showing the principle of a vibration pick-up in which no use is made of a fixed point outside the vibrating object. The relative deviation x of the mass m with respect to the housing H is measured, and furnishes a measure for the absolute deviation y of the housing (i.e. of the vibrating object).

spring, r the coefficient of damping prevailing, then the following differential equation holds for the relative displacement x of the mass with respect to the vibrating object:

$$m \frac{d^2 (x - y)}{dt^2} + r \frac{dx}{dt} + cx = 0 \dots (1)$$

In this equation y is the required deviation of the object investigated, while x can be measured directly. With the sinusoidal vibration

$$y = y_0 \cos \omega t$$

in the stationary state x becomes

$$x = x_0 \cos (\omega t - \varphi), \dots (2)$$

where

$$x_0 = y_0 \frac{(\omega/\omega_0)^2}{\sqrt{4 D^2 (\omega/\omega_0)^2 + (1 - (\omega/\omega_0)^2)^2}} \dots (3)$$

and

$$\operatorname{tg} \varphi = \frac{2 D \omega/\omega_0}{1 - (\omega/\omega_0)^2} \dots (4)$$

In these expressions $\omega_0 = \sqrt{c/m} = 2\pi$ times the resonance frequency of the undamped vibrating system and $D = r/2 \omega_0 m$, the so-called damping factor.

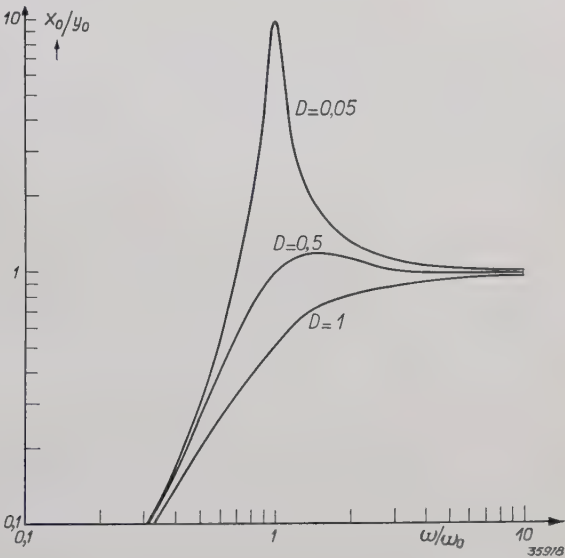


Fig. 2. Frequency characteristics of a pick-up on the principle of fig. 1, for different values of the damping factor D . At frequencies $\omega/2\pi$, which are far enough above the resonance frequency $\omega_0/2\pi$, the relative amplitude x_0 to be measured is practically equal to the absolute amplitude y_0 of the object.

In fig. 2 the ratio x_0/y_0 given by (3) is plotted as a function of the frequency for different values of the damping factor D . It may be seen that at frequencies sufficiently far above the resonance frequency $\omega_0/2\pi$, the ratio x_0/y_0 is constant and equal to unity: the mass m , due to its inertia, then remains practically at rest and thus behaves as if it were fastened to a fixed point outside the vibrating object ¹).

¹) The considerations given here are valid for all cases in which vibrations must be recorded and reproduced, thus also for microphone, gramophone pick-up, etc. A comparison with the laryngophone which was described in this periodical 5, 6, 1940, is particularly instructive. In that case also the "direct" and the "indirect" method of driving were compared and, as in this case, the indirect method was chosen. In that case, however, it was a question of the quadratic variation of the ratio x_0/y_0 as a function of the frequency, which is obtained at frequencies below the resonance frequency.

In the technical application of a vibration pick-up one is often concerned with rotating engines whose speed generally lies between 120 and 3 000 r.p.m. The fundamental frequencies of the expected vibrations may therefore be very low (several c/s). It is therefore desirable that the flat part of the frequency characteristic of fig. 2 should extend as far as possible toward the low frequencies. For this purpose the vibration pick-up must have as low a characteristic frequency as possible, and it is advisable to choose a value $D \approx 0.5$ for the damping factor.

Construction of the vibration pick-up

The principle illustrated diagrammatically in fig. 1 is realized in the following way in the Philips vibration pick-up (see fig. 3). The mass m is formed

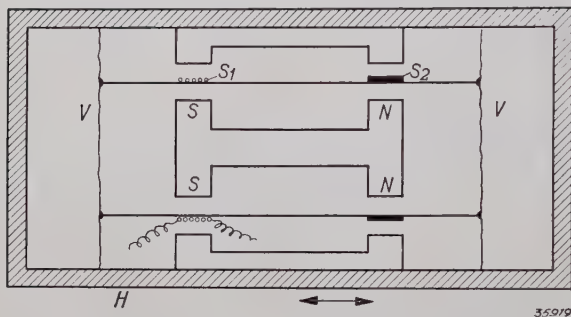


Fig. 3. Cross section of the electrodynamic vibration pick-up (very much simplified). The coils S_1 and S_2 move in the ring-shaped air gaps of a magnetic circuit which is excited by a permanent magnet. These coils are connected with each other and hung on two membranous springs V . S_1 provides the output voltage, S_2 (a copper ring) the desired damping force.

mainly by two coils S_1 and S_2 fastened to each other, which are suspended in a cylindrical housing by means of two membranous springs. The housing shares in the movement of the vibrating object. The coils can move in two ring-shaped air gaps of a permanent magnet fastened to the housing. The coil S_1 provides the desired output voltage; the coil S_2 consists of a closed ring, and the current induced in this ring gives rise to the desired damping force (second term of equation (1)).

In making the design it was kept in mind that the vibration pick-up should be able to be used in any desired position. When the pick-up is turned from the horizontal to the vertical position the coils will be displaced over a distance x_m which is given by

$$c x_m = m g,$$

(g is the acceleration due to gravity), and thus

$$x_m = g/\omega_0^2. \quad (5)$$

For a linear relation between voltage and devia-

tion, the coils must always intersect the same magnetic flux and therefore too great a variation from the position of rest of the coils would obviously lead to very uneconomical constructions. It follows from equation (5) that a lower limit is thereby prescribed for the characteristic frequency ω_0 to be chosen. The pick-up here described was constructed for a maximum throw of the coils of 3.75 mm, while it was required to be able to measure vibration amplitudes up to 2 mm. The permissible variation x_m from the position of rest is thus 1.75 mm, so that according to (5) $\omega_0/2\pi$ could be made equal to 12 c/s.

While the ratio c/m is determined in this way, further consideration shows that the total mass m of the moving system must be made as small as possible. It may easily be deduced that the damping coefficient r (equation (1)) is proportional to the volume v of the damping ring and to the square of the field strength H_2 in the air gap²⁾. Thus the damping factor D becomes

$$D = \frac{r}{2 \omega_0 m} \sim \frac{H_2^2 v}{m} \quad (6)$$

Since, except for a certain factor given by the required play of the ring in the gap, v is equal to the volume of the air gap, $H_2^2 v$ is actually the total magnetic energy, and therefore proportional to the quantity of magnet steel. In order to obtain the desired damping factor D therefore ($D \approx 0.5$), when ω_0 is once chosen, less magnet steel is necessary the smaller m is. Now a limitation of the quantity of magnet steel needed is very much desired, not only for economic reasons, but also to keep the whole vibration pick-up as small and light as possible, so that the movement of the object being investigated cannot be affected by the application of the pick-up. Obviously a type of magnet steel will be chosen which has the highest possible magnetic energy per cubic centimetre.

A limit is set to the reduction in size of the pick-up mainly by the requirements relating to the sensitivity demanded. The voltage induced in the

²⁾ If l is the length of the coil (circumference of the ring) in cm, H the field in gauss, then the induced voltage in volts is

$$e = 10^{-8} l \cdot H \cdot dx/dt.$$

This causes a current $i = e/R$ (R is the electrical resistance of the ring) and hereby a retarding force

$$K = 0.1 \cdot H \cdot i \cdot l = 0.1 \cdot H \cdot l \cdot e/R.$$

By filling in e and $R = \rho \cdot l/q$ (ρ = the specific resistance, q the diameter of the ring) one obtains

$$K = \frac{10^{-9} \cdot H^2 \cdot v}{\rho} \cdot \frac{dx}{dt} = r \frac{dx}{dt}.$$

coil S_1 is

$$e = l \cdot H_1 \cdot \frac{dx}{dt} \cdot 10^{-8} \text{ volts, (7)}$$

where l (cm) is the length of wire and H_1 (gauss) the field strength in the gap in which coil S_1 moves. In order to obtain a given sensitivity $e/dx/dt$ with a minimum amount of magnet steel (magnetic energy $H_1^2 v_1$), the volume v_1 of the air gap, and thus that of the coil, will be made as small as possible, and the length of wire l as great as possible. This means a thin wire and many windings. Attempts in this direction are, however, limited by the requirements that the wire must be able to be wound without difficulty, and that the self-induction of the coil (which is proportional to the diameter of the coil and to the square of the number of turns) must be kept so low that the resonance between the self-induction of the coil and the characteristic capacity of the coil plus the capacity of the connecting cable will lie far enough above the frequency region in which the measurements are being done. In this way one is bound to a given coil volume which cannot be reduced, and thereby not only is the amount of magnet steel required to obtain the field H_1 prescribed, but, because of the contribution of the voltage coil to the mass m in equation (6), the amount of steel necessary for the field H_2 in which the damping ring moves is also prescribed to a certain extent.

If m is made as small as possible, then for a given characteristic frequency, c must also become small, i.e. the springs must be very weak in the direction of vibration. In a direction perpendicular to this, however, they must be very stiff in order to guarantee a satisfactory centred motion of the coils in the ringshaped air gaps. This is achieved by the use of membranous springs with which a relatively slight lateral play of the coils in the air gaps suffices. Nevertheless, this play is again a reason why the whole system cannot be made too small. With a proportional reduction in size of all the other dimensions the ineffectual part of the volume of the gap becomes more and more important.

The oscillogram obtained

The EMF e excited in the coil S_1 is proportional to the velocity dx/dt at which the coil moves. If therefore we apply the voltage of the coil directly to a cathode ray oscillograph, we obtain an image of the momentary values of the vibration velocity. Such a velocity oscillogram is indeed often used in the investigation of vibrations of acoustic frequencies, since the velocity provides a better meas-

ure of the sound caused by such vibrations than the deviation. In general, however, the mechanical engineer will be more interested in the deviation itself. A voltage proportional to the deviation x is obtained by applying the voltage e of the coil to the simple circuit shown in fig. 4. If $R \gg 1/\omega C$, then

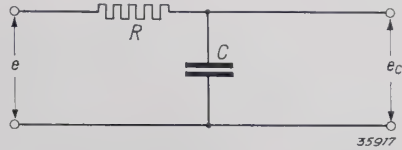


Fig. 4. "Integrating element". If the voltage e (output voltage of the vibration pick-up) is proportional to the velocity dx/dt of the vibrating object, then the voltage e_c is proportional to the deviation x if $R \gg 1/\omega C$. By applying the voltage e_c to a cathode ray oscillograph the form of the vibration in question is made visible on the fluorescent screen.

the current i through the condenser is practically equal to e/R , and the voltage on the condenser becomes:

$$e_c = \frac{1}{C} \int i \, dt = \frac{1}{RC} \int \text{const.} \cdot \frac{dx}{dt} \, dt = \text{const.}' \cdot x.$$

The voltage e_c applied to the cathode ray oscillograph thus gives an oscillogram of the deviations.

In the case of purely sinusoidal vibrations the velocity and deviation oscillograms obtained give a correct picture of the motion of the vibrating object. This is, however, not immediately the case when the vibration possesses harmonics, since in that case for faithful reproduction, it is necessary that not only the amplitude relations but also the relative phase differences of the components should be retained. The first requirement is satisfied when all the frequencies occurring fall within the flat part of the characteristic (fig. 2). The second condition means that the phase shift (φ in equation (4) with in

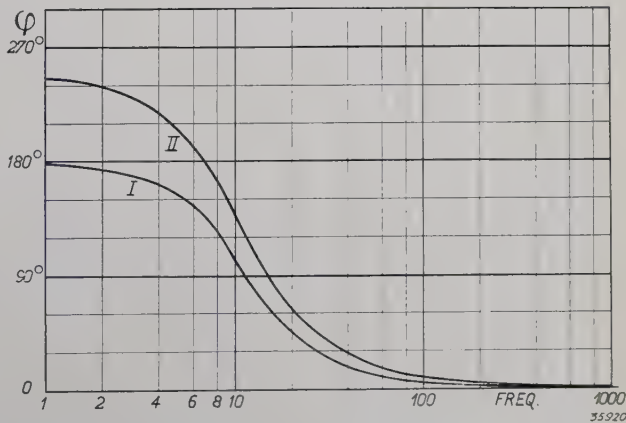


Fig. 5. Phase shift φ of the oscillographic image obtained, compared with the original vibration, as a function of the frequency (c/s). Curve I holds for the velocity oscillogram (φ is here given by equation (4), in which $D = 0.48$ and $\omega_0 = 2\pi \cdot 12$), curve II for the deviation oscillogram.

addition, for the deviation oscillogram, the phase shift in the circuit of fig. 4) must be the same for all frequencies occurring, which is the case only at relatively high frequencies, see fig. 5. The influence of phase shifts may not be simply neglected in this case, as is customary in acoustics, since for the destructive action and the disturbing effect it is just the peak values of the deviation, which depend closely upon the phase relation between the harmonics, which are most important. Fig. 6 illustrates the differences which may occur between the oscillogram and the original vibration. These differences must certainly be taken into account in judging and interpreting the oscillograms.

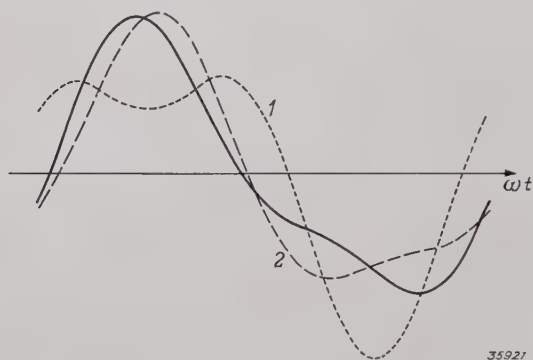


Fig. 6. The housing of the vibration pick-up may vibrate according to the relation: $x = \sin \omega t + 0.3 \cdot \sin (2\omega t - 45^\circ)$; full-line curve. According to the value of ω , the oscillogram obtained with the oscillograph GM 5 520 will deviate more or less from this curve. At $\omega/2\pi = 10$ c/s the broken-line curve 1 is obtained, at $\omega/2\pi = 25$ c/s, the broken-line curve 2.

Another distortion of the oscillogram might occur due to a deviation from the linearity of the flexibility of the spring assumed in equation (1). With a horizontal direction of motion the flexibility is indeed found not to be perfectly linear, due to an unavoidable very slight sagging of the membranous springs. The effect of this, however, is hardly appreciable: at the highest amplitudes to be measured (in the horizontal direction 3.75 mm, see above) maximum deviations of a few per cent occur in the sine tops.

The method of measurement and the enlargement obtained

In order not only to study the nature of the vibrations but also to determine them quantitatively, the following method is used. While the voltage e_c is applied to the cathode ray oscillograph, the time base is switched off so that a vertical stripe of a definite length appears on the screen. Then instead of e_c , an A.C. voltage is applied to the oscillograph with the help of a potentiometer through which an accurately determined alternating current

from the mains flows. The A.C. voltage must be such that a stripe of the same length is obtained. The potentiometer is calibrated directly in microns (vibration amplitude). In the same way, by omitting the integrating element fig. 4, the velocity amplitude can be determined.

The calibration of the potentiometer is only valid for the flat part of the frequency characteristic. For lower frequencies the result must be multiplied by a correction factor derived from the characteristic. Since for different individual vibration pick-ups the characteristics vary somewhat due to an unavoidable slight divergence in the properties of the springs and magnets, etc., upon manufacture the curve of the correction factors of each individual pick-up is recorded and accompanies the pick-up. Actually two correction curves are used, one for the approximately vertical position of the pick-up and one for the approximately horizontal position. The small difference between the two curves may be ascribed to the slight sagging of the membranous springs already mentioned. In fig. 7 an example of such a correction curve is reproduced. Above about 50 c/s no correction is necessary, for frequencies between about 10 and 50 c/s it is still relatively small, and only at still lower frequencies it is necessary to know the frequency accurately for satisfactory measurement. This can be determined with the oscillograph.

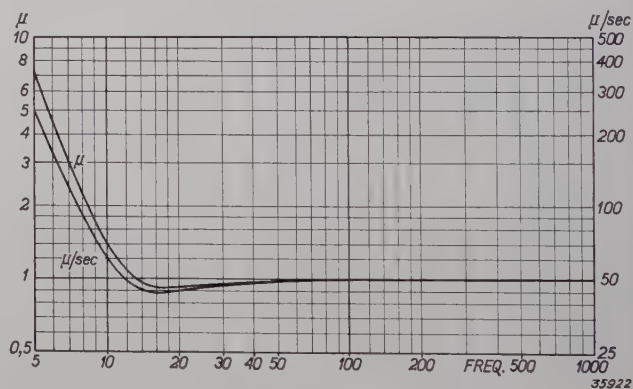


Fig. 7. One of the individually recorded correction curves. This furnishes the factor by which the reading on the calibrated potentiometer must be multiplied for every frequency in order to obtain the true amplitude (left-hand scale) or the velocity amplitude (right-hand scale).

In the method of measurement described it is tacitly assumed that the cathode ray oscillograph is just as sensitive to the frequency of the vibration to be investigated as to that of the comparison voltage (50 c/s). In the case of the cathode ray oscillograph GM 3 152 previously described in this periodical³⁾ this is true down to frequencies of about

³⁾ Philips techn. Rev. 4, 198, 1939.

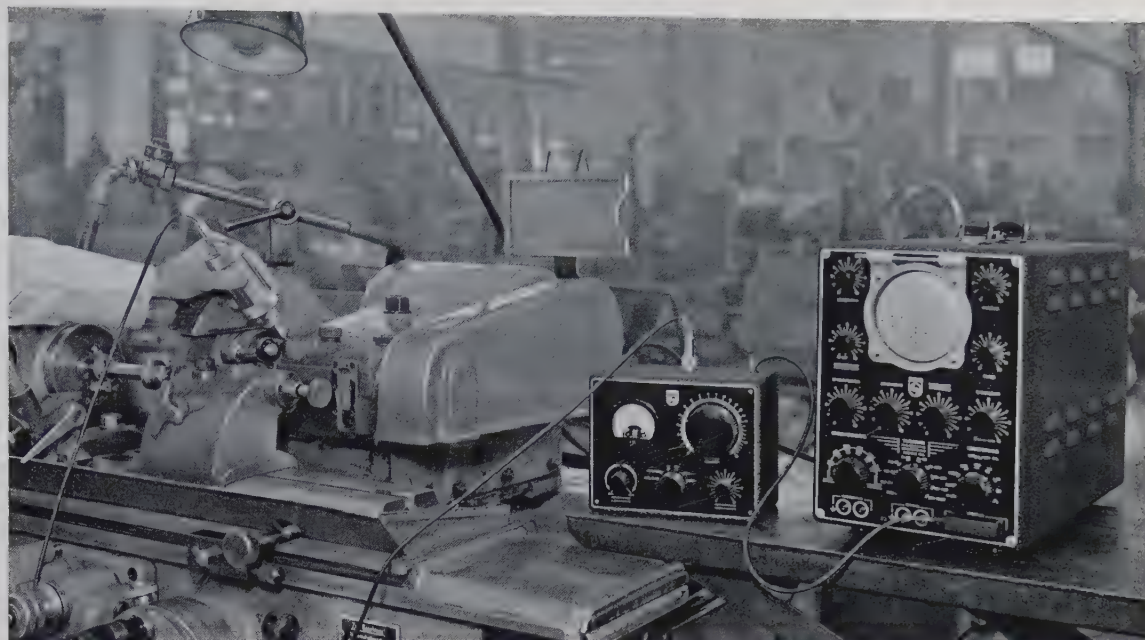


Fig. 8. Complete apparatus for vibration testing with the pick-up GM 5 520. The latter in this case is pressed with a short steel rod against the machine being investigated. (It was here a question of investigating the effect of a lack of balance in a grinding machine on the accuracy of the work). On the right the cathode ray oscillograph GM 3 156 and the box containing the integrating element, the calibrated potentiometer for the determination of the amplitudes and other components.

10 c/s, with the new oscillograph GM 3 156, this is true even down to 0.3 c/s.

The vibration pick-up in combination with the integrating element gives, in the flat part of the frequency characteristic, an output voltage of 1 mV (peak value) for an amplitude of 1 micron (and for a velocity amplitude of 50 microns/s). On the screen of the oscillograph GM 3 156 one obtains with this voltage a stripe 7 mm long (double amplitude) when the highest amplification is used. The vibration being investigated is thus delineated with an enlargement of 3 500 times. When the oscillograph GM 3 152 is used the enlargement is smaller by a factor of about 6. The accuracy of reading in the case of the comparative method described may be estimated at about 1 mm in the length of the stripe.

In measurements in the neighbourhood of the resonance frequency the results are slightly affected by the temperature of the vibration pick-up. This effect is based upon the dependence on temperature of the resistance of the damping ring, whereby the damping factor which determines the shape of the frequency characteristic near the resonance may change somewhat. The frequency characteristics are recorded at 20° C. Measurements at 12 c/s then give values about 4 per cent too high with 10° increase in temperature, while toward higher and lower frequencies the temperature effect quickly disappears.

In *fig. 8* a photograph is given of a complete measuring arrangement. In the left-hand box standing beside the cathode ray oscillograph and

connected by means of a shielded cable to the vibration pick-up, are the integrating element, the potentiometer, the necessary switches and other components.

The application of the pick-up to the vibrating object

The housing of the vibration pick-up must follow the motion of the vibrating object which is being investigated. When it is a question of low frequencies, below 100 c/s, for example, it is sufficient to press the pick-up against the vibrating surface with the hand. The long axis of the pick-up must be in the direction of vibration, since the pick-up only reacts to the vibration component in its axial direction. Use can also be made of this characteristic in order to discover the direction of vibration if it is not already known. For the case in which the direction of vibration is parallel to the surface against which the pick-up can be pressed there must be sufficient friction between the surface and the housing of the pick-up. For this purpose the housing is provided with two milled rings. (*fig. 9a*).

For the investigation of the movement of various points which may be difficult to reach, a long steel rod can be used, which can be screwed into the pick-up, and with which the object can be gone over point by point (*fig. 9b*). The long rod is also useful for vibration measurements on electromotors and the like, in order to keep the vibration pick-up at a distance from any stray magnetic fields. Although

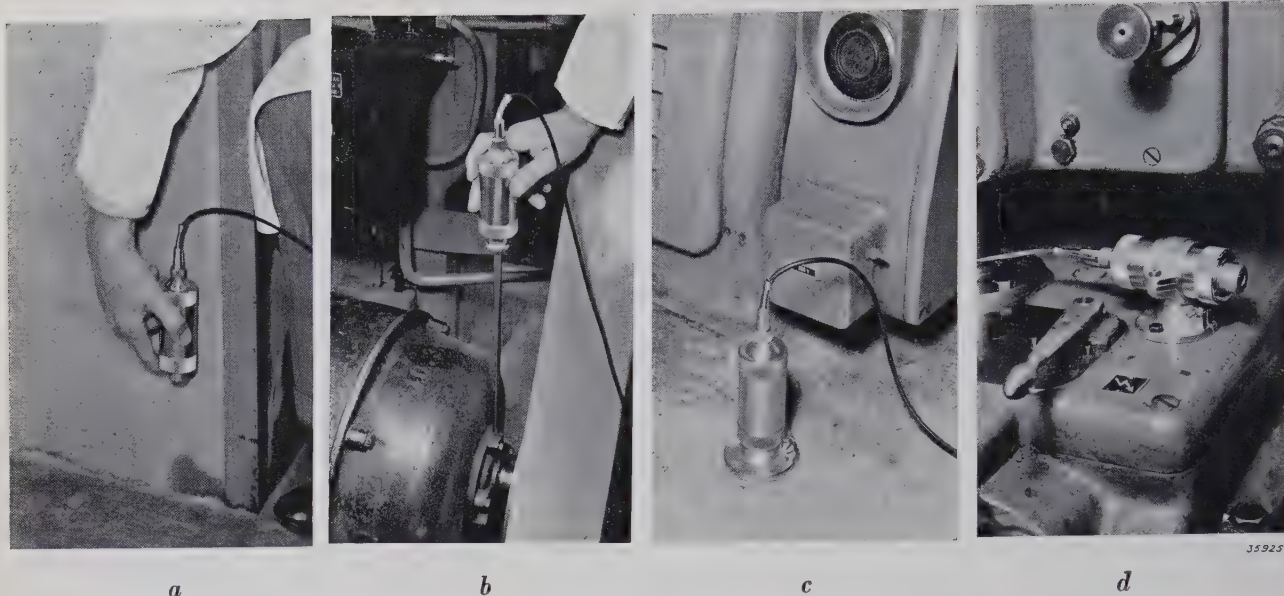


Fig. 9 *a-d*. Different methods, in which the vibration pick-up may be fastened to the vibrating object.

the iron case of the pick-up provides satisfactory magnetic protection (the field strength of an external field at the position of the coil becomes about 30 times smaller than it would be without this shielding), nevertheless, due to the large number of windings of the pick-up coil, measuring errors might occur: an external alternating field of 1 gauss in the direction of length of the coil at 50 c/s causes a voltage at the output of the integrating element of $\frac{1}{4}$ mV.

For going over the vibrating object point by point it is very advantageous that the pick-up possesses relatively strong damping (damping factor $D = 0.48$). The stationary vibration given by equations (2) to (4) is always preceded by a starting oscillation whenever the pick-up is applied, which dies out proportionally to $\exp(-\omega_0 Dt)$. With $\omega_0 = 2\pi \cdot 12$ and $D = 0.48$, it is found that this factor decreases in less than $1/5$ sec to $1/1000$, so that the oscillogram obtained is almost immediately stationary.

Attention has already been called to the fact that the motion of the vibrating object may not be affected by the addition of the mass of the pick-up. The pick-up here described weighs 580 grams, which weight may usually be entirely neglected in the case of the objects commonly occurring in machine construction and structural work. For the investigation of smaller objects a lighter weight, *i.e.* a still smaller pick-up would be desirable. This would be obtained, however, according to the above considerations, at the expense of the sensitivity of the pick-up.

In investigations which extend over a period of

time, such for instance as the balancing of motors or setting up engines so as to be free of vibration, it is easier not to apply the vibration pick-up with the hand each time, but to fasten it to the object. This can be done by means of a base plate (*fig. 9c*) which can, if necessary, be screwed to the vibrating surface and when the pick-up must be parallel to the surface it can be done with a clamp (*fig. 9d*).

Fastening by means of a base plate and screws is particularly suitable when vibrations of higher frequencies are to be investigated. The surface layer of the vibrating object together with the mass of the pick-up forms a vibration system by itself, whose characteristic frequency must lie above the frequency region being investigated if the results are not to be quite incorrect. A soft surface layer or a possible layer of paint or grease may result in a low characteristic frequency: this becomes higher, however, the greater the pressure with which the pick-up is applied to the surface.

In order to investigate in more detail the different methods of fastening, we made use of a massive block which was set vibrating by a powerful loud speaker system, and upon which, in a small cavity, a miniature example of the ordinary vibration pick-up was rigidly fastened. The motion of the block was measured by this means, while the result was compared with that obtained with an ordinary pick-up fastened to the block in different ways. It was found that the combination applied for tangential vibrations: pick-up in clamp, clamp in base plate, with well tightened screws, can be used up to frequencies of 200 c/s. When the steel rod or the milled edges of the housing are used, measure-

ments to about 500 c/s can be made, while in the case in which the pick-up is clamped on to the base plate (fig. 9c) and screwed to the vibrating surface it is certain that the pick-up can faithfully follow vibrations of 1 000 c/s and higher. In all cases a rigid, hard surface of the vibrating object is assumed.

Examples of application

In the above a number of possibilities of application have been mentioned in passing. We shall here discuss two examples in more detail.

The first example ⁴⁾ relates to the balancing of a high-speed aggregate. A compressor for coking-oven gases, driven by a steam turbine wheel with 4 800 r.p.m. was mounted on a relatively thin shaft, in order to make the characteristic frequencies of the possible bending vibrations lower than the number of revolutions when in operation. Such a system must be balanced, not only statically, but also dynamically, which is usually done at a relatively low number of revolutions. Due to the thin shaft, however, at the operating speed considerable bending and, with it new lack of balance, can occur, which is not present at low speeds. This could easily be controlled by fastening the vibration pick-up here described to the housing of the turbine, and measuring the vibrations occurring. The dotted-line curve of fig. 10 was first obtained: the balance obtained at low speed was actually found to be unsatisfactory. By shifting the balancing weights in such a way that the axis experienced as small a bending load as possible, the full-line curve was finally obtained: in normal operation practically no more vibration is present.

As a second example we may mention an inves-

tigation of vibration machines for testing the life of lamps. In testing electric lamps as to their resistance to vibration, frames are used which are brought into vibration by a motor with an ex-centric rotating mass. In order to obtain comparable results it is very important that all the lamp holders in the frames of the different vibration machines should vibrate with the same amplitude, not only in the fundamental frequency

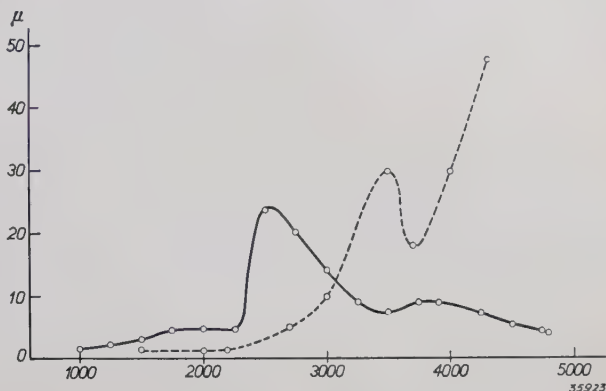


Fig. 10. Vibrations of the housing of a turbo-compressor, as a function of the speed (r.p.m.). In the case of the broken-line curve the balance was inadequate for the operating speed (4 800 r.p.m.), the balancing was thus continued until the full-line curve was obtained (N.V. Werkspoor).

but also in any possible harmonics. With the pick-up described we have studied this for various vibration machines. In the case of one machine the same amplitude of the fundamental frequency was found at all the lamp holders in the frame; it was, however, also found that there was a fairly strong seventh harmonic whose amplitude deviated several per cent in different holders. In the case of another machine the higher harmonic was lacking. It is clear that in judging the lifetime tests such differences must be taken into account. For removing these differences a vibration investigation such as here described furnishes the necessary information.

⁴⁾ We are indebted for the data of this example, which was encountered in the work of the N.V. Werkspoor, to Ir. M. J. Visser of the department for vibration investigation of that company.

ADSORPTION PHENOMENA AT METAL CONTACTS

by J. J. WENT.

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The electrical resistance of metal contacts can be divided into two parts, a "convergence resistance", which is determined by internal properties of the contact material, and a "transition resistance", which depends upon the properties of the surface of contact. In this article the transition resistance is studied of clean metal contacts, particularly of molybdenum. By heating the contact surfaces in a vacuum to temperatures of 1500—1600° C the transition resistance can be made to disappear completely. A study is made of the way in which the transition resistance of a contact cleaned in this way changes when the surfaces of contact are exposed to oxygen at room temperature and at -160° C. Conclusions may be drawn from the observations about the adsorption phenomena at metal surfaces.

In almost every piece of electrical apparatus there are numerous places where the electrical current must pass from one electrical conductor to another which is pressed against it with a certain pressure. In this transition the electric current in general experiences a resistance of from several thousandths of an ohm to twenty or thirty ohms, depending upon the nature of the contact. In practice it is desirable to make this resistance as small as possible.

In an earlier article in this periodical¹⁾ a discussion was given of the phenomena which determine the resistance of a contact. The resistance was divided into two components: the convergence resistance R_u which occurs in the interior of the contact materials due to the fact that the current lines of force must be constricted in the very small contact surface, and the transition resistance R_0 proper, which occurs at the surface of contact itself. In that case it was chiefly the convergence resistance R_u which was dealt with, and its dependence upon the pressure of contact and the hardness of the material of the contact. In this article we shall consider somewhat more closely the transition resistance R_0 . The investigation of this transition resistance is not only of technical interest, but is, moreover, found to furnish surprising insight into the adsorption phenomena at the surface of the contact material. It is mainly from this point of view that the subject will be treated in what follows.

The method of measurement

In order to be able to measure the transition resistance satisfactorily it is of importance to choose the experimental conditions such that the transition resistance R_0 between the surface of contact is considerably larger than the convergence resistance R_u . This necessity leads to measuring conditions

which are exactly opposite to the conditions which are striven for in the practical technical use of contacts. If a is the radius of the surface of contact, assumed to be circular, then the convergence resistance R_u is proportional to $1/a$, as was explained in the article already referred to. The transition resistance on the other hand is inversely proportional to the area of the surface of contact and thus proportional to $1/a^2$. The ratio R_u/R_0 , which must be made as small as possible for the investigation in question, is therefore proportional to a . The radius a must therefore be as small as possible, which, for our investigations, also involves the advantage that the absolute value of the resistance is also relatively large, and therefore easy to measure. In the case of technical contacts, on the other hand, every attempt is made to keep the absolute value of the resistance as low as possible, and thus to make the radius a as large as possible.

In order to keep the radius of the surface of contact small, low contact pressures must be used and, moreover, a contact material must be chosen with a relatively great hardness. In this case two molybdenum rods were used as contact pieces, and they were laid crosswise over each other with a contact pressure of a few grams. In order to reduce the ratio R_u/R_0 still more, part of the measurements were done at a low temperature (-160° C). At this temperature the specific resistance of molybdenum, and with it the proportional convergence resistance, is considerably lower than at room temperature, while the transition resistance changes only slightly with the temperature²⁾.

Several observations

It was at first ascertained whether it is possible to make the transition resistance disappear completely by cleaning the contact surface thoroughly.

¹⁾ Philips techn. Rev., 4, 332, 1939.

²⁾ Cf. R. Holm and W. Meissner, Z. Phys. 74, 715, 1932.

For this purpose the molybdenum rods were placed in a vacuum tube and heated for a long time at a temperature of about 1500°C . The contact resistance measured at room temperature was indeed found to become smaller and smaller and finally to approach a final value which differs only slightly from the theoretically calculated pure convergence resistance. This would mean that the transition resistance has practically disappeared.

A confirmation of this result could be obtained by ascertaining how the contact resistance depends upon the temperature. The contact resistance is composed of the convergence resistance which changes very much with temperature, and the transition resistance which is practically independent of the temperature. As the contribution of the transition resistance becomes smaller, the temperature coefficient of the total contact resistance will therefore have to increase in order finally to reach a value which is equal to that of the specific resistance of the contact material.

This is found experimentally to hold. According as the total contact resistance decreases, its temperature coefficient increases. The ratio $R_{20^{\circ}} : R_{160^{\circ}}$, which was taken as a measure of the temperature coefficient, finally reaches a value of 2.1, while the ratio of the specific resistances of molybdenum at these temperatures amounts to 2.3. If it is assumed that R_0 is entirely independent of the temperature, it follows from these values that the residual transition temperature at room temperature amounts at the most to 10 per cent of the convergence resistance.

After a perfectly clean contact had been obtained in this way, oxygen at a temperature of -160°C was admitted to the tube in order to find out what effect it has upon the transition temperature. The result is reproduced in *fig. 1*. The transition resistance already exhibits considerable increase at

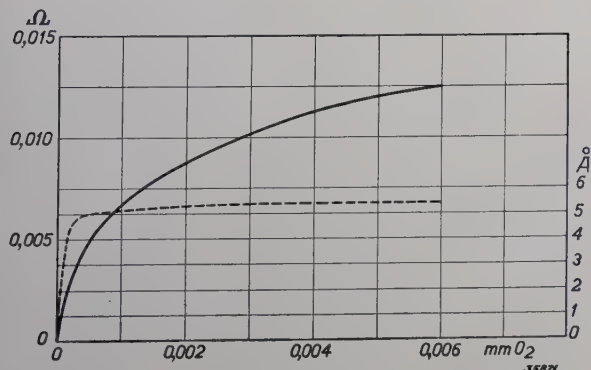


Fig. 1. Full-line: contact resistance as a function of the oxygen pressure for a molybdenum contact at -160°C . Broken line: the distance between the parts of the contact derived from the above resistance, calculated for a work function of 3.8 volts.

oxygen pressures of the order of 10^{-4} mm, and at a pressure of about 0.01 mm it reaches a saturation value which amounts to about 0.013 ohm with the contact in question. The relation between the resistance and the pressure is easily reversible: when the oxygen is pumped off, the resistance changes according to the same curve as during admittance of the oxygen, and finally disappears entirely. No time lag was observed in reaching the resistance corresponding to each pressure. It may be concluded from this that the contact resistance adapts itself to the oxygen pressure in less than 10 sec. (*i.e.* the time necessary for the measurement).

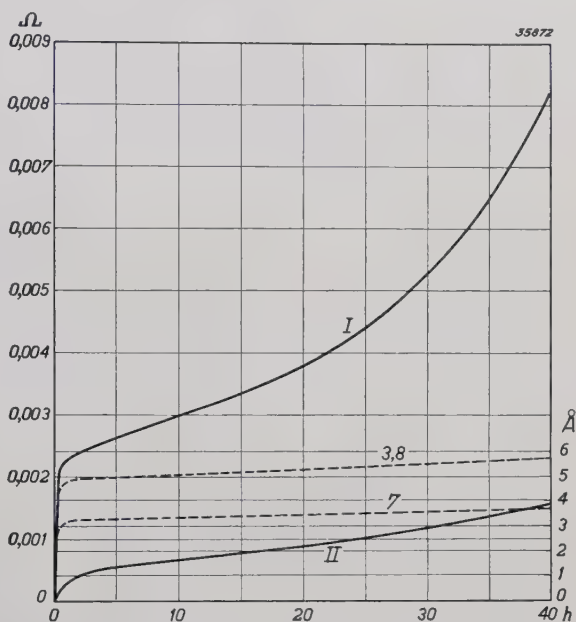


Fig. 2. Curve I: variation of the transition resistance of a molybdenum contact as a function of the time, where the contact surfaces are exposed to oxygen at room temperature.

Curve II: the part of the contact resistance which remains when the oxygen is pumped off at the time indicated. The curve is recorded by evacuating at certain moments during the exposure to oxygen, carrying out the measurement and then again admitting oxygen.

Broken-line curves: the distance between the contact points calculated from curve II, when a work function of 3.8 volts and 7 volts, respectively, is assumed.

If the same experiments are repeated at room temperature, the results are less simple. In the first place the contact resistance is not a function of the pressure alone, but depends very much upon the time during which the contact metals have been exposed to the oxygen (see *fig. 2* curve I). Moreover, the relation between oxygen pressure and contact resistance is not reversible: if at a given moment the oxygen is pumped off, a certain resistance persists, which is given by curve II of *fig. 2*. It may be seen that the two curves as functions of the time rise steadily without it being possible to speak of saturation.

Explanation and completion of the observations

The change in the contact resistance upon the admission of oxygen indicates that the metal surfaces are attacked in one way or another by the oxygen. Upon this assumption, in order to understand the difference between the behaviour at low temperature and at room temperature, at least two processes must be assumed to take place: a reversible process which proceeds rapidly, and an irreversible process which only occurs at a higher temperature, and proceeds much more slowly. Both processes are of such a nature that the molybdenum becomes covered with a layer which has a resistance of the order of 10^{-8} to 10^{-9} ohm/cm².

For further identification of these processes one must begin with the existing information about the adsorption of gases on metals.

a) Van der Waals adsorption

If a metal surface is exposed to oxygen, it becomes covered with a monomolecular layer of oxygen. The molecules of this oxygen layer are bound to the metal surface by relatively weak forces of attraction, which are always present between molecules, even though the molecules exhibit no chemical activity with respect to each other. These forces are called van der Waals forces, because they are found to be of the same type as those which van der Waals considered responsible for the condensation of gases.

Although the strength of the van der Waals bond generally amounts to only a few per cent of that of the chemical bond, it is large enough to give rise to a dense covering of the metal with oxygen molecules at an oxygen pressure of less than 0.01 mm. The result is that the two pieces of metal cannot approach each other more closely than to a distance equal to twice the thickness of an oxygen molecule. It is obvious that the electrons passing from one part of the contact to the other will experience a certain resistance in passing through this space.

In order to calculate the magnitude of this resistance, we consider the contact as consisting simply of two pieces of metal situated at a definite distance from each other, and take no account of the fact that the space between these pieces of metal is filled with oxygen. The electrons which must pass from one part of the contact to the other must then leave the metal and enter the empty space, for which a certain φ (work function) is necessary, and they may then enter the second part of the contact, whereby the work function is regained.

Since the kinetic energy of practically all the electrons in the metal is smaller than the work function, it might be expected that the electrons would not be able to leave the metal, so that the contact resistance would be infinitely large. With a distance between the electrodes which is not too small (for instance larger than 10^{-5} cm) this is indeed true. If, however, the distance becomes smaller than 10^{-6} cm, electrons with a kinetic energy smaller than the work function also have a

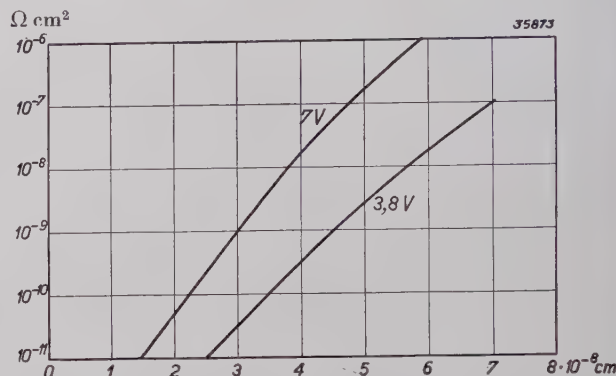


Fig. 3. Relation between the distance between two pieces of metal and the transition resistance for different values of the work function. At a first approximation this relation is expressed by equation (1). The figure gives a closer approximation.

certain chance of passing from one part of the contact to the other. This is a result of the wave nature of matter which makes itself felt when the motion of electrons is considered over distances which are not very large compared with their wave lengths³). If on the basis of wave mechanics one calculates the transition resistance of a contact with a surface of contact O , a distance d between the parts of the contact and a work function φ , then as a first approximation one obtains:

$$R_0 = \frac{h^2 d}{\sqrt{2m\varphi} O} \exp\left(\frac{\pi d}{h} \sqrt{2m\varphi}\right), \quad \cdot \cdot \quad (1)$$

where h is Planck's constant and m the mass of the electron. In fig. 3 the relation is shown between R_0 , O and d for different values of the work function φ . When it is kept in mind that the surface of contact of contacts is in general only of the order of 10^{-8} cm², it may be seen that an appreciable conductivity between two metal surfaces can only occur for distances d between these contacts up to about 10^{-7} cm.

In the case of molybdenum contacts the work function has a value of about 3.8 volts. If one

³) A qualitative explanation of this phenomenon was given in this periodical in an article on blocking-layer rectifiers: Philips techn. Rev. 4, 100, 1939.

calculates the distance between the metal surfaces for this value from the transition resistance observed, one finds a variation as a function of the oxygen pressure such as is indicated with a broken line in fig. 1. It is striking that the distance between the metal surfaces seems already to approach its final value at a considerably lower oxygen pressure: between 0.0005 and 0.06 mm oxygen pressure the distance d changes by only 19 per cent, the transition resistance R_0 , however, is more than doubled by this change.

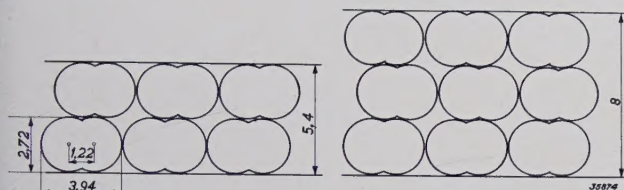


Fig. 4. A distance of 5.4 Å provides space for a double layer of oxygen molecules; a distance of 8 Å provides space for a threefold layer of oxygen molecules.

The final value of the distance d amounts to 5.4 Å. Since the thickness of an oxygen molecule, according to research with the help of electron diffraction, is 2.72 Å, this agrees exactly with what would be expected if each of the parts of the contact were covered with a monomolecular layer of oxygen (see fig. 4). A contact resistance about 100 times greater is sometimes observed at high oxygen pressures. This corresponds to a distance $d = 8$ Å. Apparently in these cases one of the parts of the contact is also covered with a second layer of oxygen ($3 \times 2.72 = 8.16$).

b) Activated adsorption

If the contact surfaces are exposed to oxygen at room temperature, as already stated a gradual increase of the contact resistance with time is observed, which upon pumping the oxygen away only gradually disappears again. Apparently the oxygen bound by van der Waals forces passes gradually over into another state in which it adheres much more strongly to the surface, so that the molecules cannot immediately be removed by evacuation.

A phenomenon by comparison with which this behaviour may be explained is known to chemistry under the name of activated adsorption. Molecules which are adsorbed by van der Waals forces are converted by a certain activation process into a state in which the bond is much stronger. In the case of oxygen, for example, it is known that in some cases the adsorbed molecules are split into atoms which are then bound chemically by the

underlayer; this chemical combination is indeed much stronger than the bond due to van der Waals forces.

A representation of this process may be given by plotting the binding energy of an oxygen molecule and of the atoms formed from it as a function of the distance between the molecule (or atom) and the surface of the metal⁴). A diagram is obtained such as that shown in fig. 5. The potential energy of the adsorbed molecule or atom is plotted vertically. For a definite distance the potential energy has a minimum, and this is at a distance from the wall at which the adsorbed particle is in equilibrium. For the atom this distance is always smaller than for the molecule, since the atom has a smaller diameter. Furthermore the depth of the minimum for the atom is considerably greater, since the chemical bond is much stronger than the bond due to van der Waals forces.

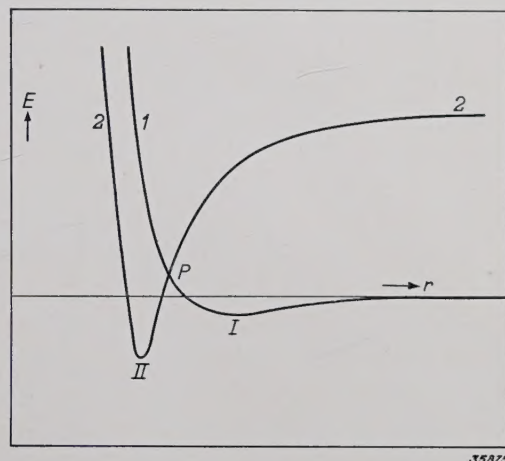


Fig. 5. Potential energy as a function of the distance from the molybdenum surface: 1 for an oxygen molecule, 2 for two oxygen atoms. The atoms are bound more firmly and at a smaller equilibrium distance from the surface than the molecules.

We now see that a molecule will first be found by van der Waals forces and thereby reach the potential minimum *I*. At a sufficiently low temperature it will remain in this minimum. At room temperature, however, the molecules are sufficiently strongly agitated to carry out vibrations, and it may occur that the point *P* is suddenly exceeded. This means that the molecule can dissociate into atoms without any further addition of energy. The atoms now behave as may be deduced from potential curve 2, i.e. they are chemically bound at a distance given by the position of the potential minimum *II*.

⁴) This view of activated adsorption was first given by J. E. Lennard Jones, Trans. Faraday Soc. 28, 333, 1932.

This distance can again be determined by calculating the distance between the parts of the contact from the contact resistance measured. The difficulty is here encountered, however, that the work function φ is not known in the case of activated adsorption. If the molybdenum surface is covered with a layer of molecules, as in the case of adsorption by van der Waals forces, then — as has been done above — it may be assumed that the work function of an electron will not differ appreciably from that of an electron from the clean molybdenum surface, which is 3.8 volts. If, however, the surface is covered with chemically bound oxygen atoms, the latter are negatively charged⁵). The electrons which leave the metal are pushed back by this negative charge and the work function is hereby increased to for instance 6 volts or more.

Since the correct value of the work function is not known, we have calculated d for two values of φ : a value of 3.8 volts, which is certainly too small, and a value of 7 volts, which is very probably too large. The broken-line curves of fig. 2 give the results; these have been derived from curve II. It is found that the thickness of the layer of oxygen no longer changes to any extent after 5 hours. With $\varphi = 3.8$ volts a distance of 5.8 Å between the parts of the contact is calculated, while with $\varphi = 7$ volts a distance of 3.8 Å is found. The actual distance is probably less than 5 Å, and in any case less than the distance which prevails with adsorption by van der Waals forces, as was also assumed in drawing the potential curves.

Migration of oxygen molecules over the surface

In the experiments described until now, when oxygen was admitted or pumped off, the parts of the contact were taken apart so that the contact surfaces could easily be reached by the surrounding oxygen molecules. If, however, the perfectly clean contacts are pressed together, and then only oxygen is admitted, it is found that at a low temperature (−160° C) no increase of the resistance occurs at all. At room temperature the resistance begins to increase gradually, much more slowly, however, than when there is direct contact between the oxygen and the molybdenum (see fig. 6).

It may be concluded from this that the molecules adsorbed by van der Waals forces remain in position at low temperatures, but at room temper-

ature they migrate over the surface and in doing this penetrate between the surfaces of contact. At the same time the above-described process of activated adsorption takes place, i.e. the molecules at a certain moment pass into the dissociated state; the thus formed oxygen atoms are bound chemically and thus their migration interrupted.

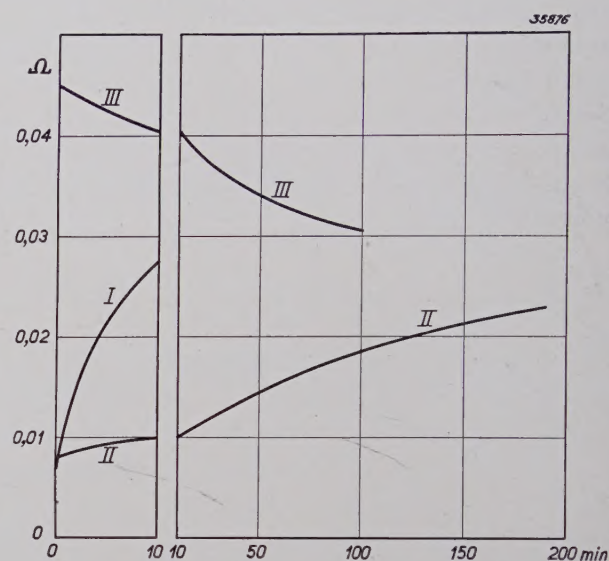


Fig. 6. Curve I: variation of the contact resistance as a function of the time, for a molybdenum contact whose parts are exposed at room temperature to oxygen and afterwards pressed together (corresponds to curve I of fig. 2).

Curve II: same as curve I for the case where the parts of the contact remain pressed together all the time, so that they cannot be immediately reached by the oxygen molecules.

Curve III: variation of the contact resistance as a function of the time after the oxygen has been pumped off, for a contact whose surfaces were exposed to oxygen and then pressed together, so that the oxygen molecules could not easily escape.

In this way the molybdenum becomes gradually covered with an atomic layer of oxygen, and this also takes place between the surfaces of contact. When this covering is complete, it might be imagined that on the top of the layer of oxygen atoms a layer of oxygen molecules might be formed which also penetrates between the surfaces of contact. This can be studied by finding out how the resistance changes when the oxygen is pumped off. If a layer of oxygen molecules were present, upon decrease in pressure this layer should creep away gradually from between the surface of contact, so that the transition resistance would decrease. If, however, the oxygen layer between the surfaces consists entirely of oxygen atoms, then even at room temperature they will remain in their places, so that the contact resistance upon pumping off the oxygen will not change at all.

This last was actually observed when the parts of the contact were exposed to oxygen for about

⁵) This has been found from investigations of the electron emission of tungsten which is chemically closely related to molybdenum.

three hours while being pressed together. It follows from this that the molecules which creep between the contact surfaces are all split up into atoms. If on the other hand the open contact is exposed to oxygen, it is found that the contact resistance, after closing the contact and pumping off the oxygen, again partially disappears, as curve *III* of fig. 6 shows. With an opened contact, therefore, a layer of molecules is apparently formed on top of the layer of oxygen atoms.

If it is desired to make the transition resistance disappear entirely, the molybdenum must be heated so highly during evacuation that the chemically bound oxygen atoms also evaporate. As was mentioned in the beginning, the melting point of

molybdenum is high enough for this to be done: heating to 1500°C gives the desired result.

What exactly happens when this is done cannot be stated with certainty. It seems as if the atomic oxygen layer does not evaporate directly, but is first transferred into a different state. If the molybdenum is heated to a lower temperature, for instance 1100°C , no decrease in the resistance is observed, but, on the contrary, a fairly considerable increase. It is possible that this may be ascribed to the formation of molecules of molybdenum oxide (MoO_3). This oxyde has a considerably higher vapour tension than molybdenum itself, so that upon heating to 1500°C the molecules can evaporate and the surface becomes perfectly clean.

STANDARDIZATION OF ACOUSTIC QUANTITIES

389.6 : 534.6.081.1

In February 1937¹⁾ tables were given in this periodical for the sound pressure and the velocities of the air particles at different sound levels, as well as for the frequency of the different musical tones. The remark was there made that it was extremely unfortunate that different standards were used in different countries by different investigators. Since this situation has recently been changed by international regulation, it will perhaps be useful to give the tables once more, brought into agreement with this regulation.

The sound level is indicated in "phons", *i.e.* the number of decibels above a definite threshold value. As threshold value, *i.e.* as the sound intensity

to which the level of zero phons is ascribed, the intensity 10^{-16} watts/cm² was decided upon at a conference in June 1937 in Paris, called together on the initiative of the C.C.I.F. (Comité Consultatif International Téléphonique). This intensity corresponds to an effective sound pressure of 2×10^{-4} dynes/cm². In *table I* the effective values of the sound pressure and of the velocity of the air particles are given for the sound levels from 0 to 120 phons. With the help of the values given for the levels from 60 to 80 phons, increasing by intervals of 1 phon, interpolation can be carried out in the main table, as explained in the accompanying text.

The regulation as to the frequencies of the musical tones was arrived at in May 1939 in London; at a meeting of one of the committees of the I.S.A. (International Federation of Standardizing Asso-

¹⁾ R. Vermeulen, Octaves and Decibels, Philips techn. Rev. 2, 47, 1937.

ciations) the frequency of *A*, upon which the tuning of musical instruments is based, was fixed at 440 c/s²). In *table II* the frequency of the other tones of the equally tempered scale is given. The last column gives the intervals for one octave.

R. Vermeulen.

²) Cf. also: Balth. van der Pol and C. C. J. Addink, The pitch of musical instruments and orchestras, Philips techn. Rev. 4, 205, 1939. In this article it is stated that the pitches practically occurring in concerts are very divergent, and that the average of the values of *A* measured lay just at 440 c/s.

Table I

Level (phons)	Intensity (W/cm ²)	Sound pressure	Air velocity
0	10 ⁻¹⁶	0,2	0,05
10	10 ⁻¹⁵	0,63	0,16
20	10 ⁻¹⁴	2	0,5
30	10 ⁻¹³	6,3	1,6
40	10 ⁻¹²	20	5
50	10 ⁻¹¹	63	16
60	10 ⁻¹⁰	0,2	50
70	10 ⁻⁹	0,63	160
80	10 ⁻⁸	2	0,05
90	10 ⁻⁷	6,3	0,16
100	10 ⁻⁶	20	0,5
110	10 ⁻⁵	63	1,6
120	10 ⁻⁴	200	5

Table I (Interpolation)

Level (phons)	Intensity (W/cm ²)	Sound pressure	Air velocity
60	1,0	0,2	50
61	1,26	0,22	56
62	1,58	0,25	63
63	2,0	0,28	71
64	2,5	0,32	79
65	3,2	0,36	89
66	4,0	0,40	100
67	5,0	0,45	112
68	6,3	0,50	126
69	8,0	0,56	140
70	10	0,63	158
71	12,6	0,71	177
72	15,8	0,80	200
73	20	0,89	220
74	25	1,00	250
75	32	11,2	280
76	40	12,6	310
77	50	14	350
78	63	16	400
79	80	18	460
80	100	20	500

Interpolation: all values are repeated every 20 phons except for a factor of a power of 10. If for instance the sound level is 27 phons, the sound intensity lies between 10⁻¹⁴ and 10⁻¹³ W/cm²; from the more detailed table for the most commonly occurring values between 60 and 80 phons, one finds at 27 + 2.20 = 67 phons the value 50; thus the result is 5.0 × 10⁻¹⁴ W/cm². In the same way the sound pressure 4.5 millidynes/cm² and the air velocity 1.12 μ/sec. are found.

Table II

Octave Tone	C ₂ -C ₁	C ₁ -C	C-c	c-c ¹	c ¹ -c ²	c ² -c ³	c ³ -c ⁴	c ⁴ -c ⁵	c ⁵ -c ⁶	c ⁶ -c ⁷	Intervalle
c	16,35	32,70	65,41	130,81	261,63	523,25	1046,5	2093,0	4186,0	8372	1,0000
cis=des	17,32	34,65	69,30	138,59	277,18	554,36	1108,7	2217,5	4434,9	8870	1,0595
d	18,35	36,71	73,42	146,83	293,67	587,33	1174,7	2349,3	4698,6	9397	1,1225
dis=es	19,45	38,89	77,78	155,56	311,13	622,26	1244,5	2489,0	4978,0	9956	1,1892
e	20,60	41,20	82,41	164,81	329,63	659,26	1318,5	2637,9	5274,0	10548	1,2599
f	21,83	43,56	87,31	174,61	349,23	698,46	1396,9	2793,8	5587,6	11175	1,3348
fis=ges	23,12	46,25	92,50	185,00	369,99	739,99	1480,0	2960,0	5919,9	11840	1,4142
g	24,50	49,00	98,00	196,00	392,00	783,99	1568,0	3136,0	6271,9	12544	1,4983
gis=as	25,96	51,91	103,83	207,65	415,30	830,61	1661,2	3322,4	6644,9	13290	1,5874
a	27,50	55,00	110,00	220,00	440,00	880,00	1760,0	3520,0	7040,0	14080	1,6818
ais=bes	29,14	58,27	116,54	233,08	466,16	932,32	1864,6	3729,3	7458,6	14917	1,7818
b	30,87	61,73	123,47	246,94	493,88	987,76	1975,5	3951,1	7902,1	15804	1,8877
c	32,70	65,41	130,81	261,63	523,25	1046,50	2093,0	4186,0	8372,0	16744	2,0000